Heavy Hadron Physics at Belle

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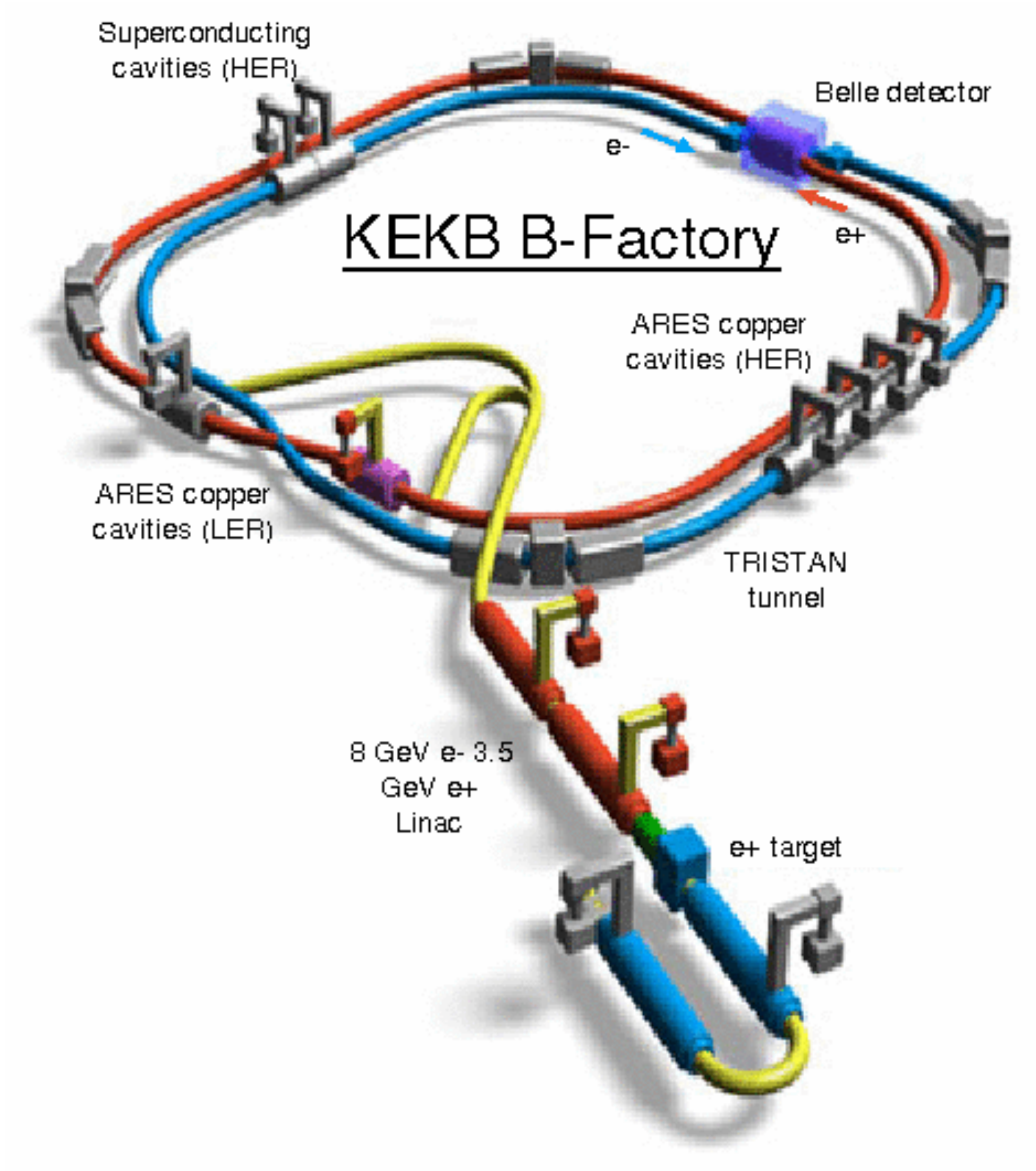
Belle Collaboration

Workshop on spectra and structures of heavy quark hadrons and nuclei
Feb. 26, 2014, KEK

Outline

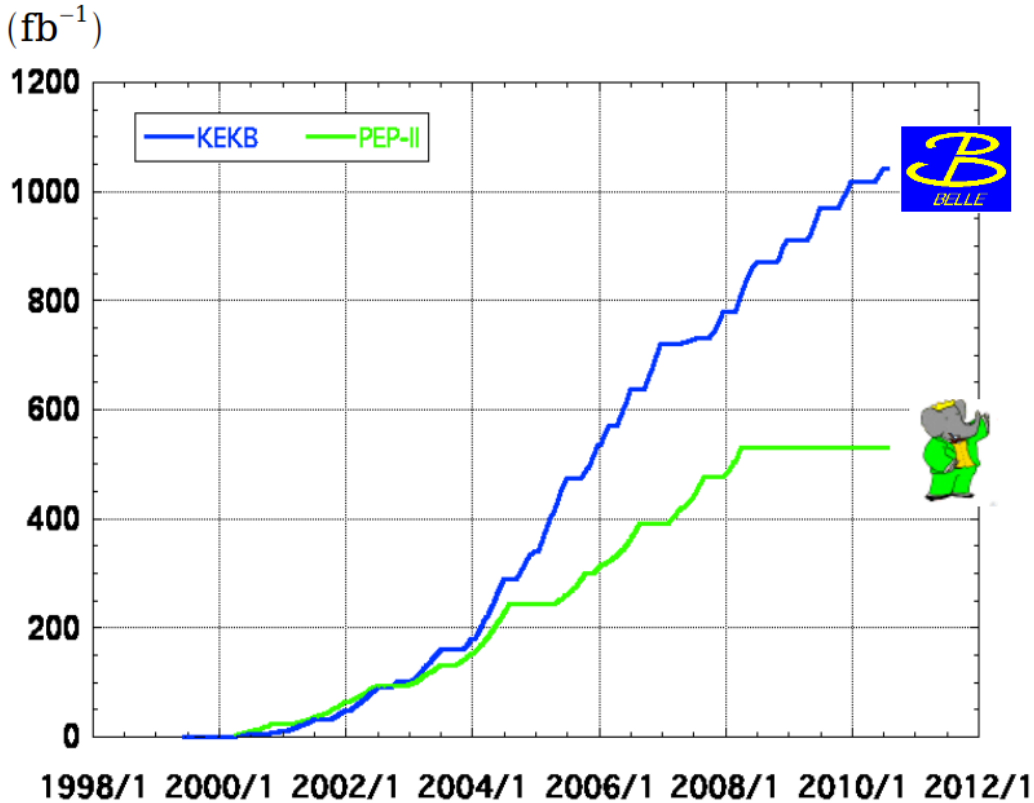
- KEK B factory
- Belle detector
- Impression of a theorist who started Belle data analysis
- NPC result: production rates of baryons
- Charmonium physics
  $\eta_c(2S)$, $Z_c(3900)$, $X(3940)$
- Bottomonium physics
  $h_b(1,2P)$, $Z_b^{\pm,0}(10610)$, $Z_b^{\pm,}(10650)$
- Charmed baryons
  $\Lambda_c(2880)$, $\Sigma_c(2800)$, $\Xi_c(3077)$
- Summary

KEK B factory



- 8GeV(e^-) ×3.5GeV(e^+)
- Peak Luminosity 2.1×10^{34} cm^{-2} s^{-1}
- Integrated luminosity 1040 fb^{-1}

Integrated luminosity of B factories



$> 1\ ab^{-1}$

On resonance:

$\Upsilon(5S)$: 121 fb^{-1}

$\Upsilon(4S)$: 711 fb^{-1}

$\Upsilon(3S)$: 3 fb^{-1}

$\Upsilon(2S)$: 25 fb^{-1}

$\Upsilon(1S)$: 6 fb^{-1}

Off reson./scan:

$\sim 100\ fb^{-1}$

$\sim 550\ fb^{-1}$

On resonance:

$\Upsilon(4S)$: 433 fb^{-1}

$\Upsilon(3S)$: 30 fb^{-1}

$\Upsilon(2S)$: 14 fb^{-1}

Off resonance:

$\sim 54\ fb^{-1}$

Cross section and luminosity

- Cross section , Unit: barn, symbol: b
  1 b = 10^{-24} cm^2
- Total cross section of $e^+e^- \to \mu^+\mu^-$

$$\sigma_{tot} = \int d\sigma = \frac{4\pi\alpha^2}{3E_{cm}^2}\sqrt{1-\frac{m_\mu^2}{E^2}}\left(1+\frac{1}{2}\frac{m_\mu^2}{E^2}\right) \cong \frac{87}{E_{cm}^2}\,nb \quad \left(E >> m_\mu\right)$$

  with E_{cm} in unit of GeV.
- Event rate = luminosity × cross section

- In the case of KEK B factory
  Event rate of $e^+e^- \to \mu^+\mu^-$
  $=87/(10.5)^2 \times 21 \sim 16.6/\text{sec}$

  Event number of $e^+e^- \to \mu^+\mu^-$
  $=87/(10.5)^2 \times(\text{nb/fb})\times 1000 \sim 8\times 10^8$

- Event number of $e^+e^- \to c\overline{c}$
  $=(2/3)^2\times N_c \times 87/(10.5)^2 \times(\text{nb/fb})\times 1000 \sim$
  1.1×10^9
  Not only B factory, but also charm factory!
- 772×10^6 B Bbar pairs

Upsilon(4S) production rate

About Upsilon(4S)

- M = 10.5794 GeV
- $J^{PC} = 1^{--}$
- Width = 20.5 MeV
- $B^+ B^-$ & $B^0 B^{0bar}$ threshold = 10.559 GeV
- B B* threshold = 10.604 GeV
- Upsilon(4S) -> $e^+ e^-$ fraction = 1.57×10^{-5}
- Upsilon(4S) -> B Bbar fraction > 96%

$$\sigma(e^+e^- \to \Upsilon(4S)) = 64\pi^3\alpha^2 \frac{|\psi(0)|^2}{M^3}\delta(E_{cm}^2 - M^2)$$

$$\Gamma(\Upsilon(4S) \to e^+e^-) = \frac{16\pi\alpha^2}{3}\frac{|\psi(0)|^2}{M^2}$$

$$\sigma(e^+e^- \to \Upsilon(4S)) = 4\pi^2 \frac{3\Gamma(\Upsilon(4S) \to e^+e^-)}{M}\delta(E_{cm}^2 - M^2)$$

$$\delta(E_{cm}^2 - M^2) \sim \frac{1}{2\pi M\Gamma_{full}}$$

at E_{cm} = M with full width of Upsilon(4S)

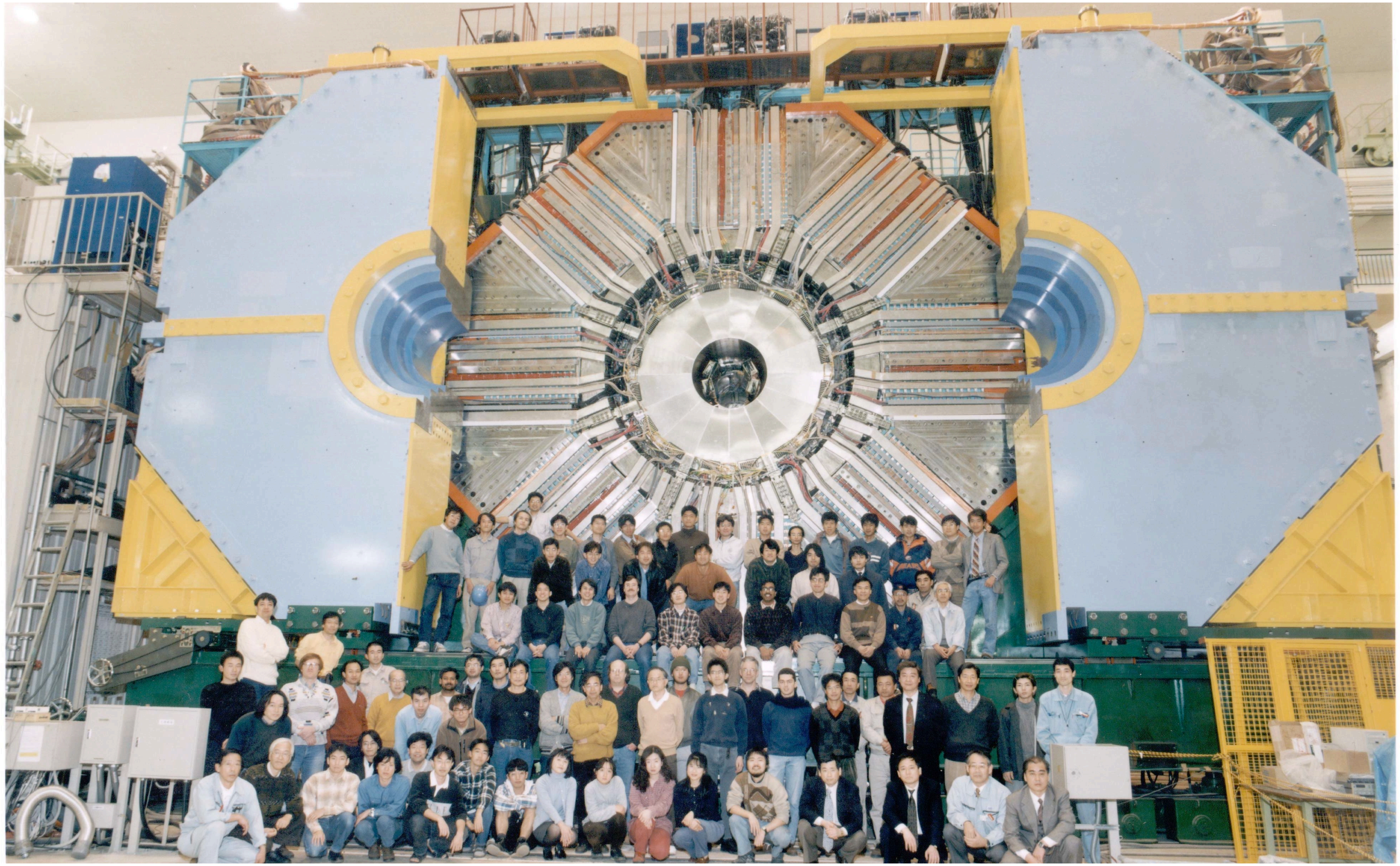
$$\sigma(e^+e^- \to \Upsilon(4S)) = \frac{6\pi}{M^2} \frac{\Gamma(\Upsilon(4S) \to e^+e^-}{\Gamma_{full}}$$

～1nb

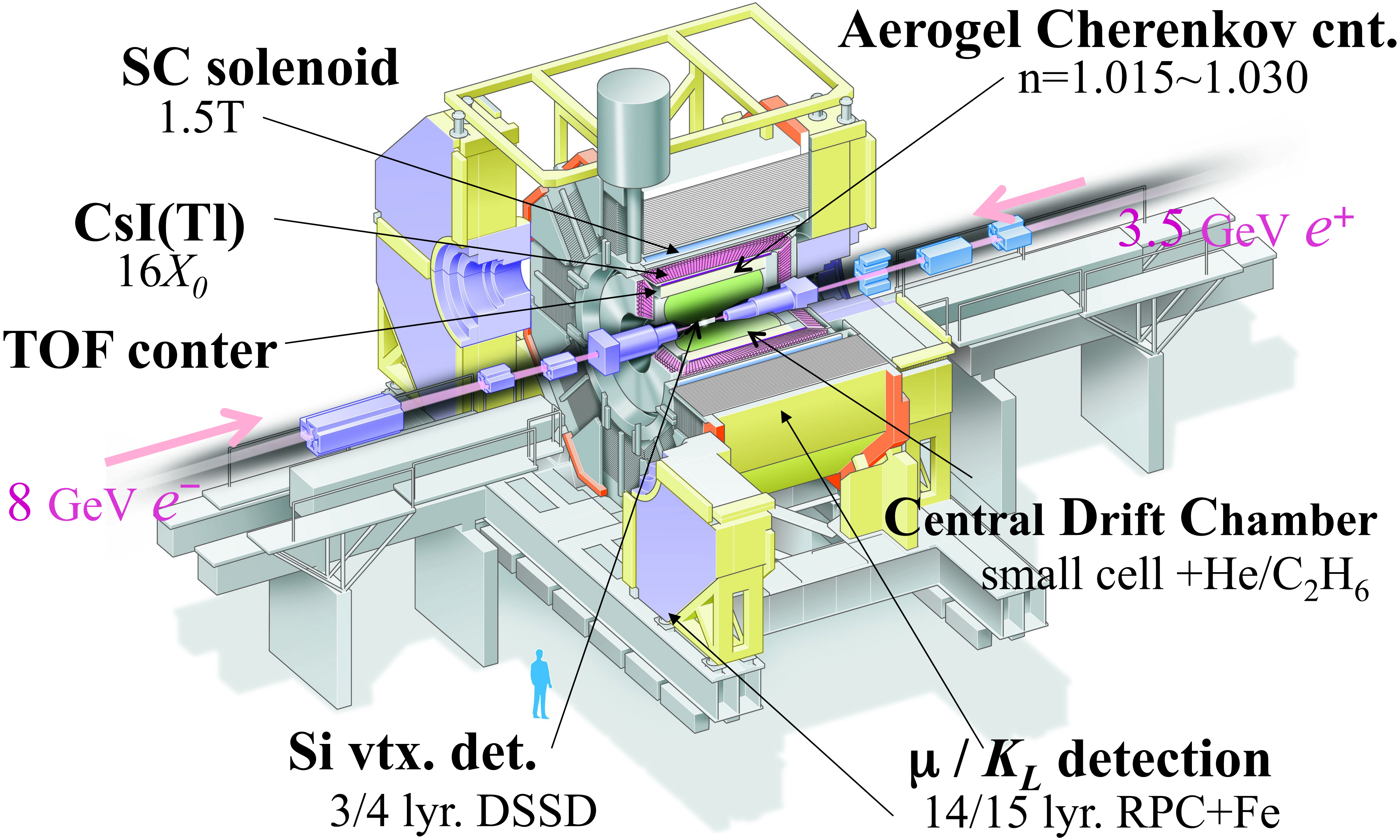
Total number of Upsilon(4S)
～ 1.1nb/fb×700 = 770 M

Observed Upsilon event number is about 770 M and the efficiency is very good ～ 100%.

Belle detector



Belle Detector



- High resolution, multipurpose, good PID, 4π spectrometer

- Loose event selection

Physics runs

Table 1. Summary of the luminosity integrated by Belle, broken down by CM energy.

Resonance	On-peak luminosity (fb^{-1})	Off-peak luminosity (fb^{-1})	Number of resonances
$\Upsilon(1S)$	5.7	1.8	102×10^6
$\Upsilon(2S)$	24.9	1.7	158×10^6
$\Upsilon(3S)$	2.9	0.25	11×10^6
$\Upsilon(4S)$ SVD1	140.0	15.6	$152 \times 10^6\ B\bar{B}$
$\Upsilon(4S)$ SVD2	571.0	73.8	$620 \times 10^6\ B\bar{B}$
$\Upsilon(5S)$	121.4	1.7	$7.1 \times 10^6\ B_s\bar{B}_s$
Scan		27.6	

Reference: J. Brodzicka et. al., PTEP, 2012, 04D001

- Off-resonance data
  60MeV below the resonance peak in order to determine the non-BB^bar background
- Energy scan data
  between $\Upsilon(4S)$ and $\Upsilon(6S)$

Data analyses at Belle

Detected particles

- photon
- electron, muon
- Charged particles:pion, kaon, proton
- Neutral particles:K_L
  $\pi^0 \to \gamma\gamma$, eta-> $\gamma\gamma$, Ks -> $\pi\pi$, $\Lambda \to p\pi$

Energy, momentum, track, vertex point

BASF(Belle Analysis Software Framework)

- Analysis code is written by C++ using Belle's original classes.
- Ks and Lambda -> reconstruction routine with vertex fitting.
- For B meson analyses, full reconstruction is done by the Neuro-computing code.

Personal impression of a theoretical hadron physicist who started Belle data analyses

Organization of Belle

- One can freely start data analysis of the subject if no one in the collaboration has not obtained physics results on that subject.
- Data analysis meetings on each subject (TDCPV, EWP, Charm, Upsilon(5S), Two photons, etc.) are organized and there, one can obtain useful suggestions for the analysis.

- One can freely read the notes of the previous analyses and leaned many things from there such as cut conditions, fitting functions, estimations of the systematics, etc.

- When one obtain some physics results on his/her analysis, one has to write his/her analysis note (called Belle note). Then, three internal referees are assigned.

- In the collaboration meeting, one has to present his/her result before opening his/her result to public. Only the approved result can be presented in the conference.

Gap between experimentalists and theorists

- Most of the theorists do not know how to estimate the systematic errors.

- In order to estimate the systematic errors, experimentalists estimate the errors in
  (1) acceptance corrections
  (2) background subtractions
  (3) fitting functions

Event Generator

- Experimentalists use the event generator to simulate the physical events.
- Using generated data, the acceptance is estimated.
- Improvement of the event generator is very important -> theorists
  (1) hadronization processes
  (2) inclusion of the new resonances and exotic hadrons

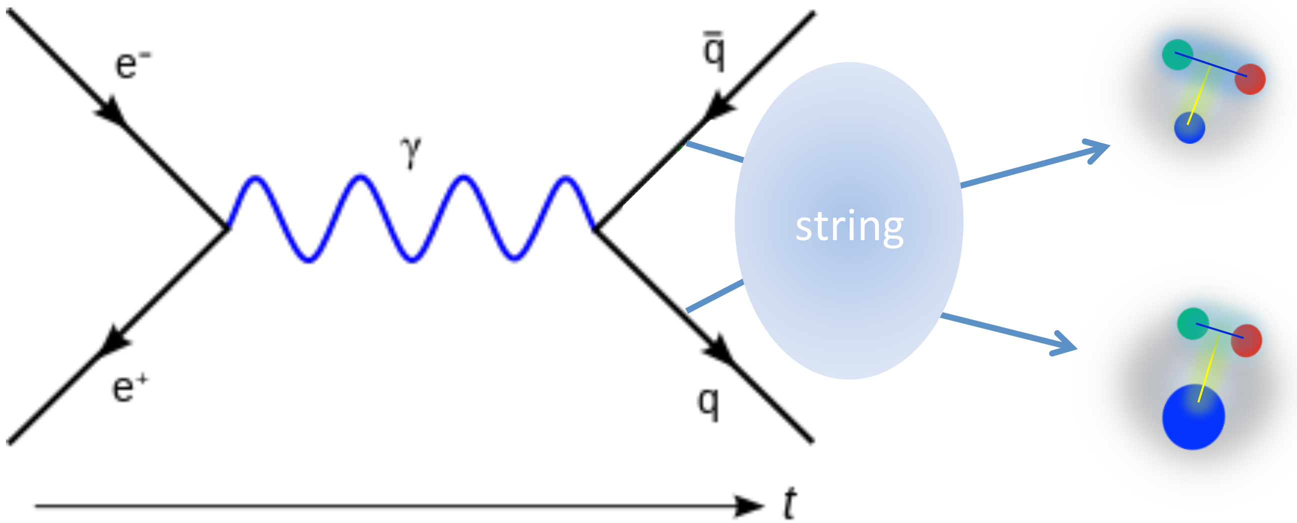
Spectral shape

- Espetially, near threshold, theoretical estimation of the spectral line shape is important.

NPC results
presented at Hadron 2013
by Sumihama-san

Production cross sections of Strange and Charmed baryons at Belle

M. Sumihama for NPC@Belle

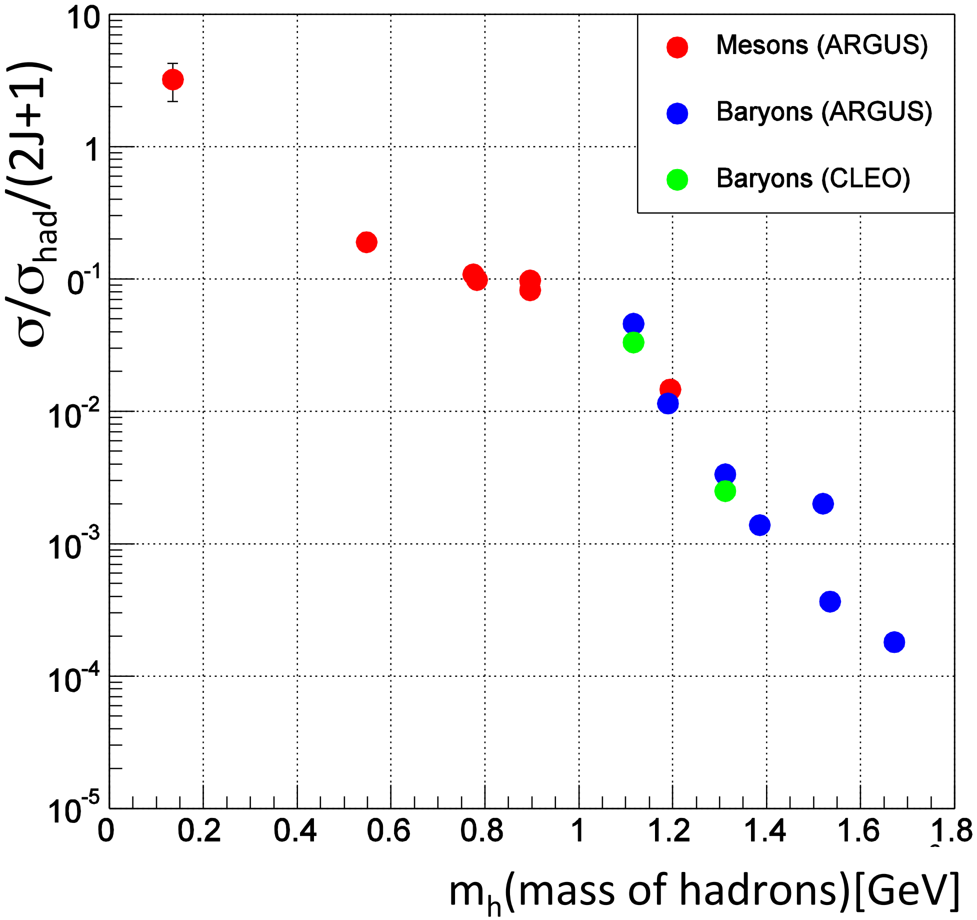


@$\sqrt{s}$ = 10.52 GeV

Production rate of baryons

Production rate $\sigma/\sigma_{had}/(2J+1) \propto \exp(-\alpha m_h)$ due to linear potential

- Slope of meson (qq^{bar}) is different from baryons (qqq).
- Slope depends on quark counting
- "4 or 5-quark state" do not lie on "3-quark state"? Λ(1405), pentaquark, Θ^+?

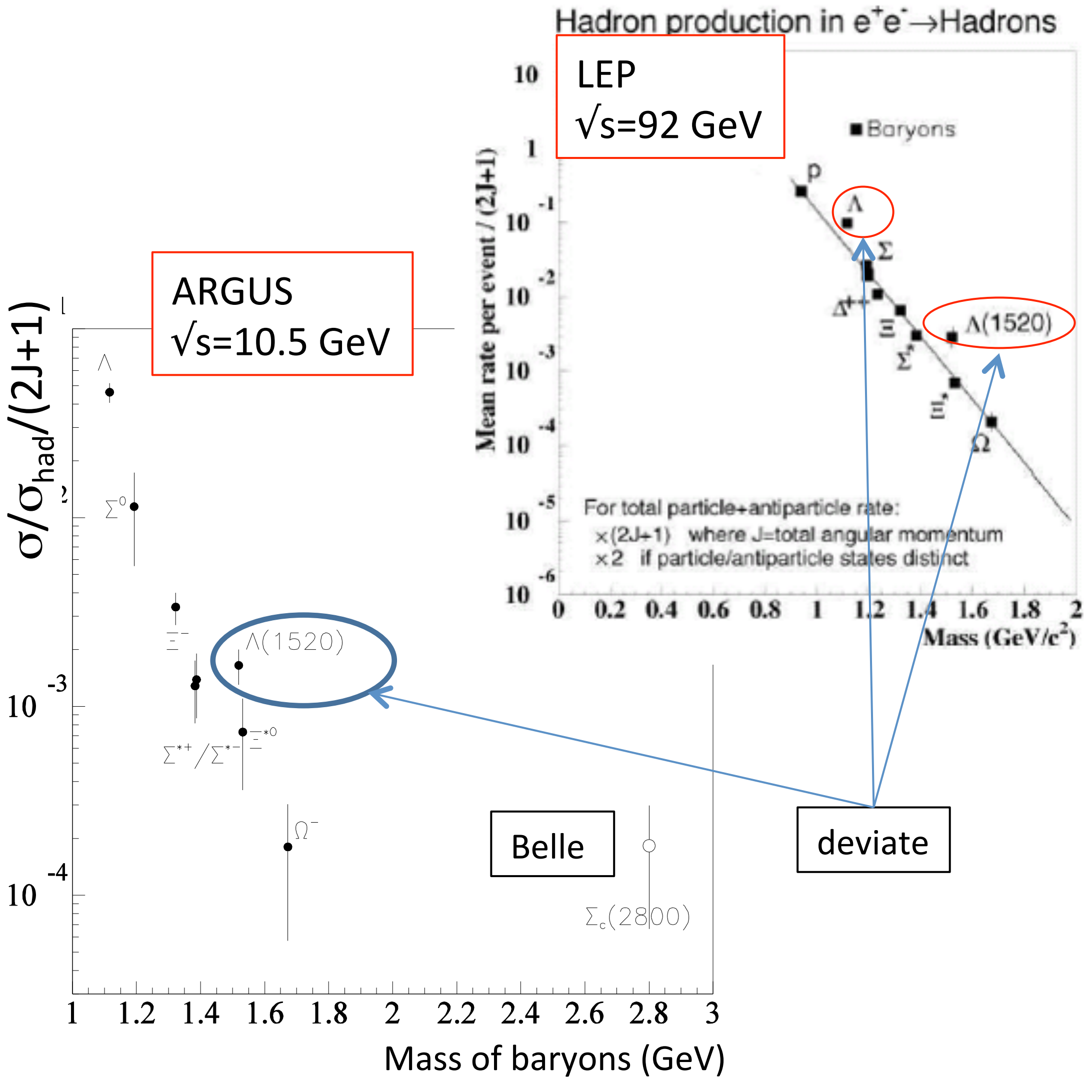


Previous data

- Λ(g.s.)/Λ(1520) deviate in LEP
  → good di-quark > bad di-quark?
  R.L.Jaffe, Phys.Rept.409:1-45,2005
- $\Lambda(1520)[3/2^-]$ deviates in ARGUS
  → $[3/2^-]$ state is special?
  → L=0 ≠ L=1 ?
  → $\Lambda(1520)\ [3/2^-]$ $\Lambda c^*(2625)[3/2^-]$
  $\Lambda(1405)\ [1/2^-]$ $\Lambda c^*(2595)[1/2^-]$

- Error bar in ARGUS is large
  → More precise data

- No series of charmed baryon
  → First systematic measurement of production rate for charmed baryons.



In this work

- Production rate is good mean to see
  not only hadronaization / fragmentation
  but also quark picture of hadrons.
- Systematic study of baryons, and search for “exotic”
  baryons in strange and charmed baryons.
- Information on diquark picture of charmed baryons
  in contrast with strange baryons.
- Λ, Σ, Σ^*, Ξ, Ω, Λ_c, Λ_c^* ,Σ_c ,Σ_c^*
  First systematic measurement for series of charmed baryons.

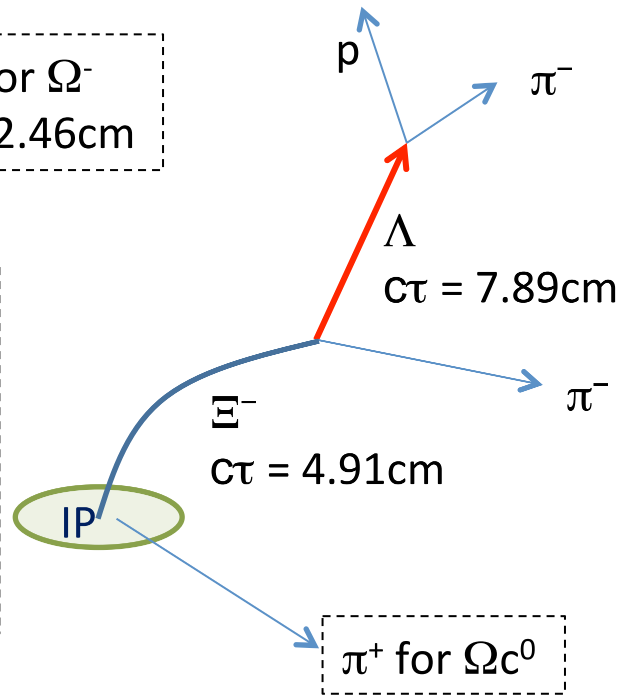
- It is interesting and important to look at the tendency
  of many hadrons by precise measurement.
  Belle data, well constructed detectors and good statistics.

Ξ^-, Ω^-, Ωc^0

Decay process analyzed in this work

- Ξ^- [dds] ◊ $\Lambda\pi^-$
- Ω^- [sss] ◊ ΛK^- + their charge conjugate conditions
- Ωc^0 [ssc] ◊ $\Omega^-\pi^+$

Same topology for Ω^-
cτ=2.46cm



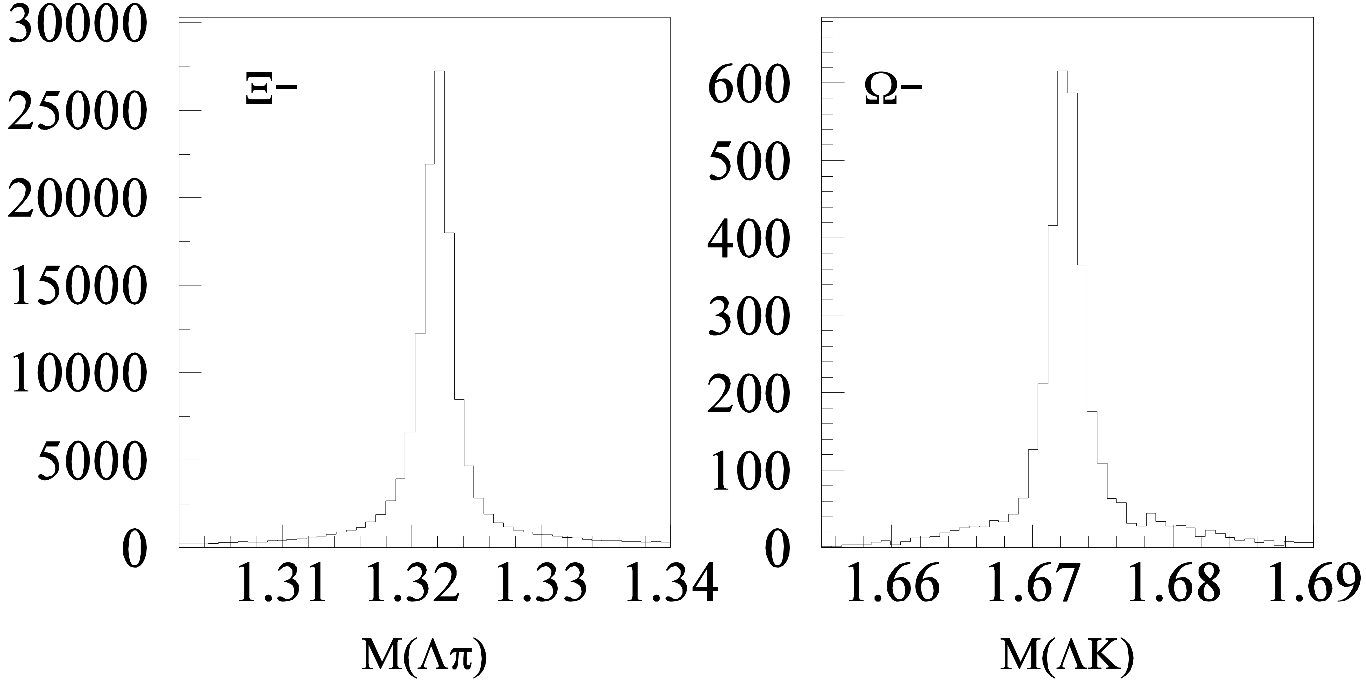
Points :

1. Ξ^- /Ω^- is produced at Interaction point(IP)
2. Ξ^- , Ω^- and Λ are long life,
   decay points are not always at IP.

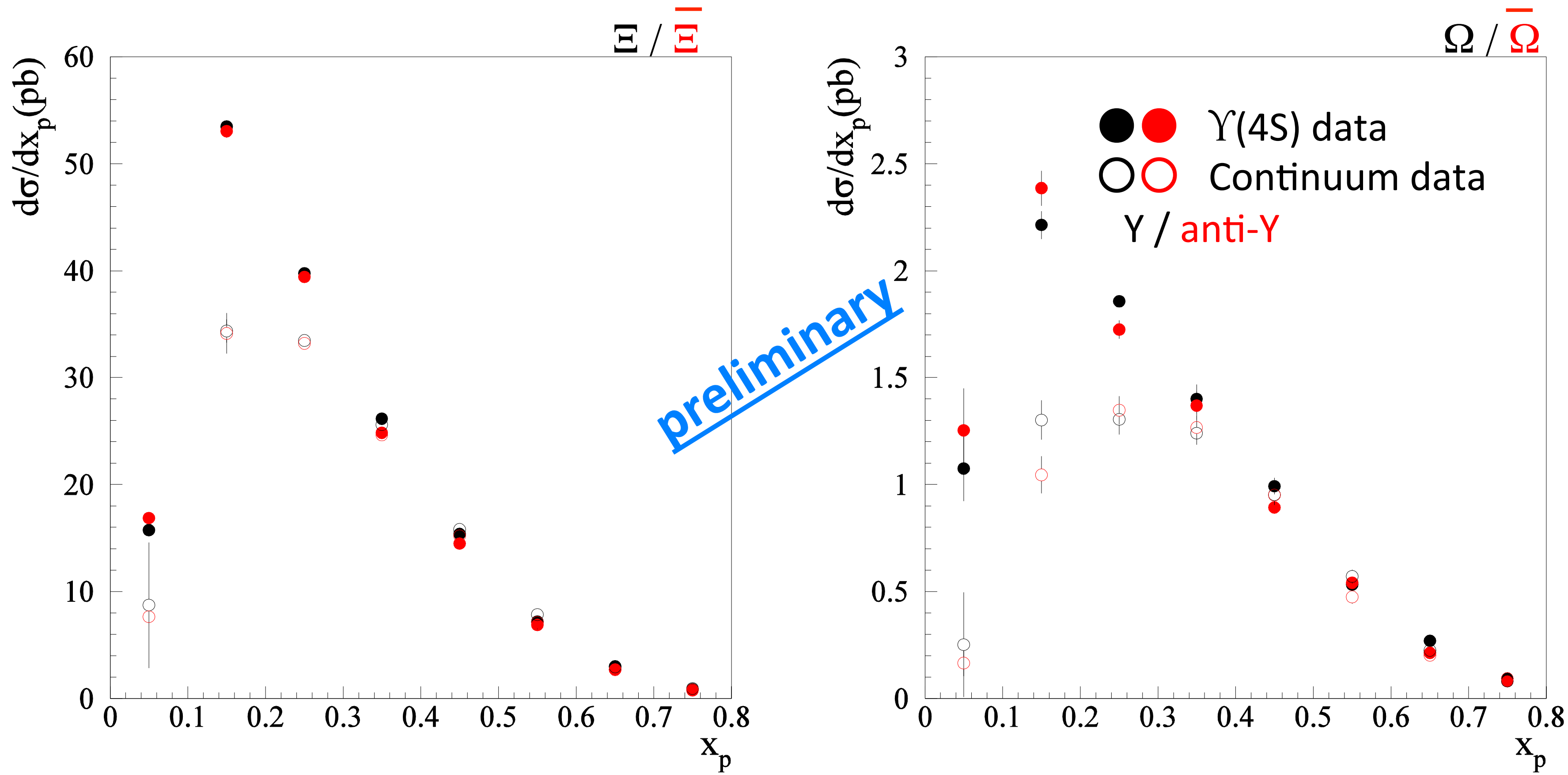
Precise vertex reconstruction is required.

Mass spectrum of Ξ⁻ and Ω⁻

Full statistics with continuum



Cross sections of Ξ and Ω



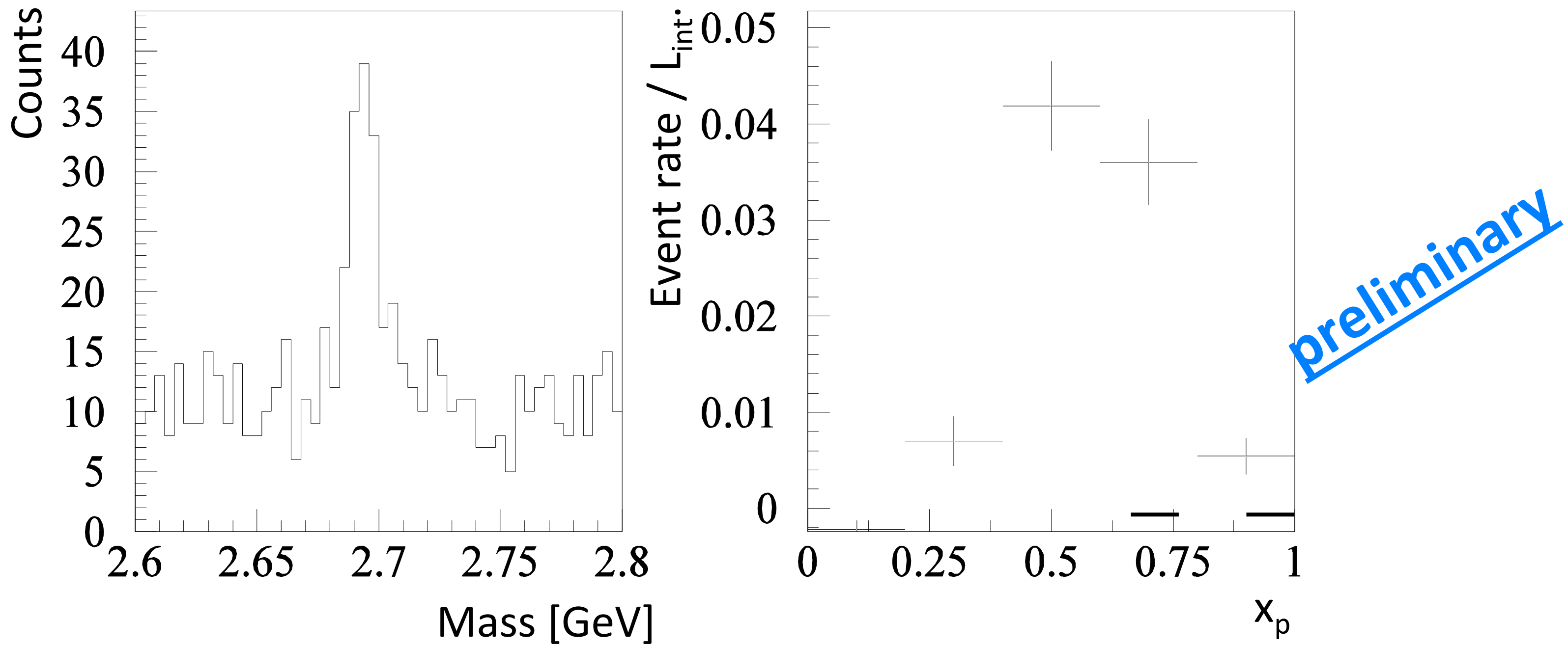
$\Xi + \Xi^{bar}$
Total cross section = 25.55 +- 0.64 pb

$\Omega + \Omega^{bar}$
Total cross section = 1.15 +- 0.32 pb

Continuum data

$\Omega c \rightarrow \Omega^{-}\pi^{+}$ +c.c.

Continuum data



σ x BR ($\Omega^{-}\pi^{+}$) + c.c. = 0.04 0.003 pb
$\Omega_c \rightarrow \Omega^{-}X$ = 0.2 pb

BR 1.25±0.5% for $\Omega^{-}X$
0.25±0.12% for $\Omega^{-}\pi^{+}$
by phenomenological calculation (ref. PDG)

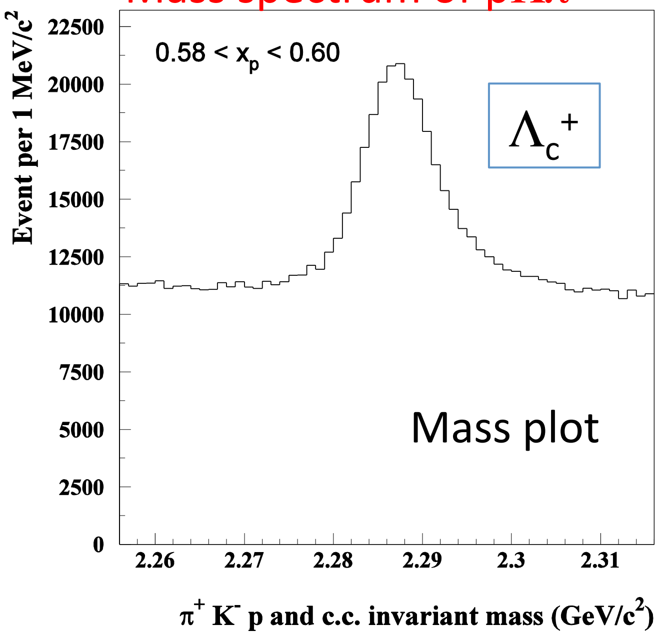
Λ_c^+, Λ_c^{*+}, Σ_c^0, and Σ_c^{*0}

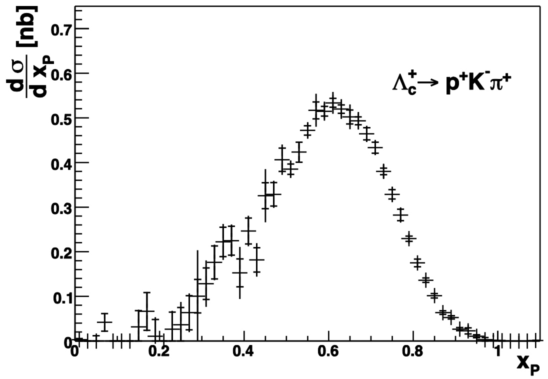
Decay process analyzed in this work

- $\Lambda_c^+ \rightarrow pK^-\pi^+$
- $\Lambda_c^*(2625) \rightarrow \Lambda_c^+ \pi^+ \pi^-$
- Σ_c^0 ◊ $\Lambda_c^+ \pi^-$
- $\Sigma_c^*(2520)$◊ $\Lambda_c^+ \pi^-$

+ c.c.

Mass spectrum of pKπ

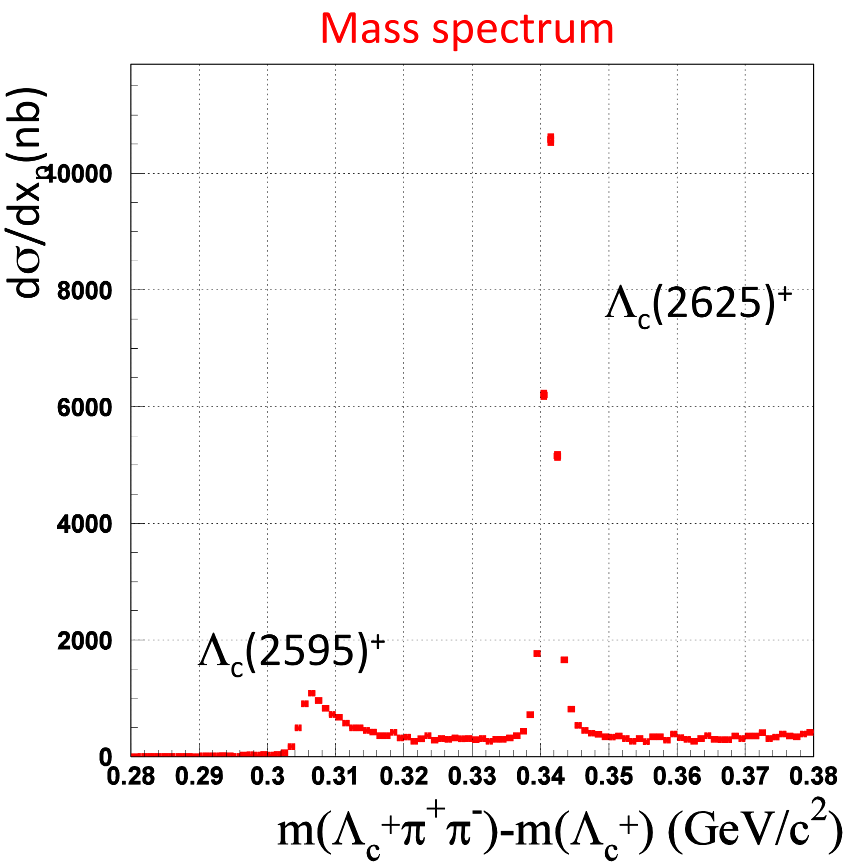




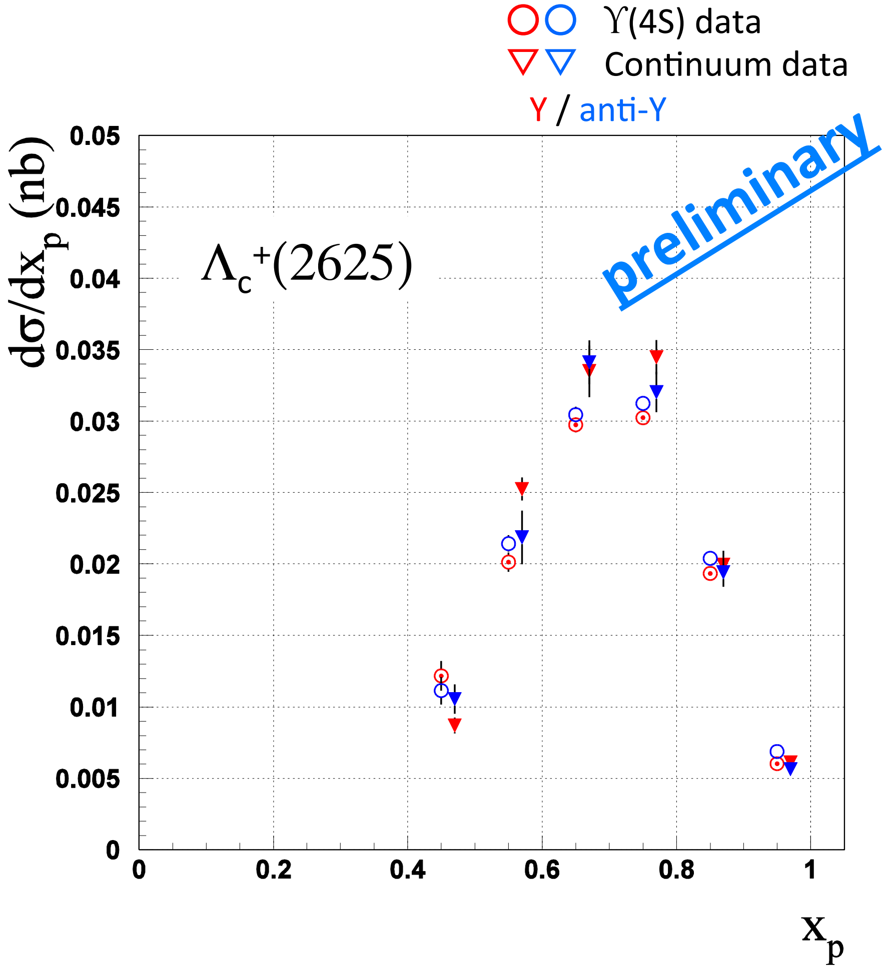
R. Seuster *et. al.* (Belle Collaboration), Phys. Rev. D **73** (2006) 032002.

- Normalization of Λ_c^+ has not been done. Normalization factor by previous Belle data →systematics
- Λ_c^*, Σ_c, Σ_c^* are reconstructed by Λ_c^+, and π or ππ.

$\Lambda_c^+(2625)$

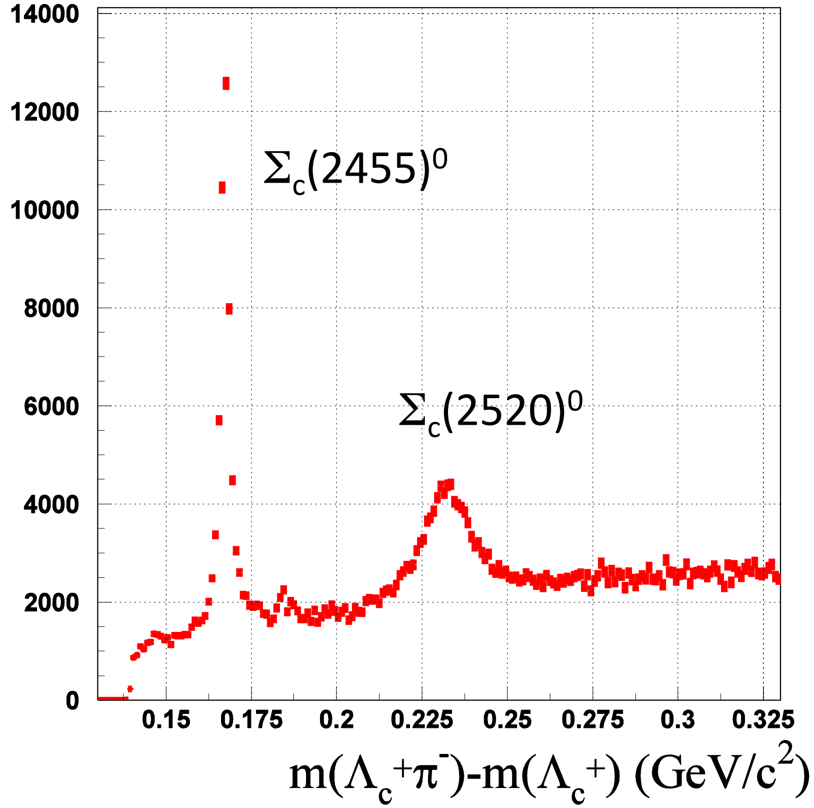


Xp



Mass spectrum of $\Sigma_c^0(2455)$, $\Sigma_c^*(2520)^0$

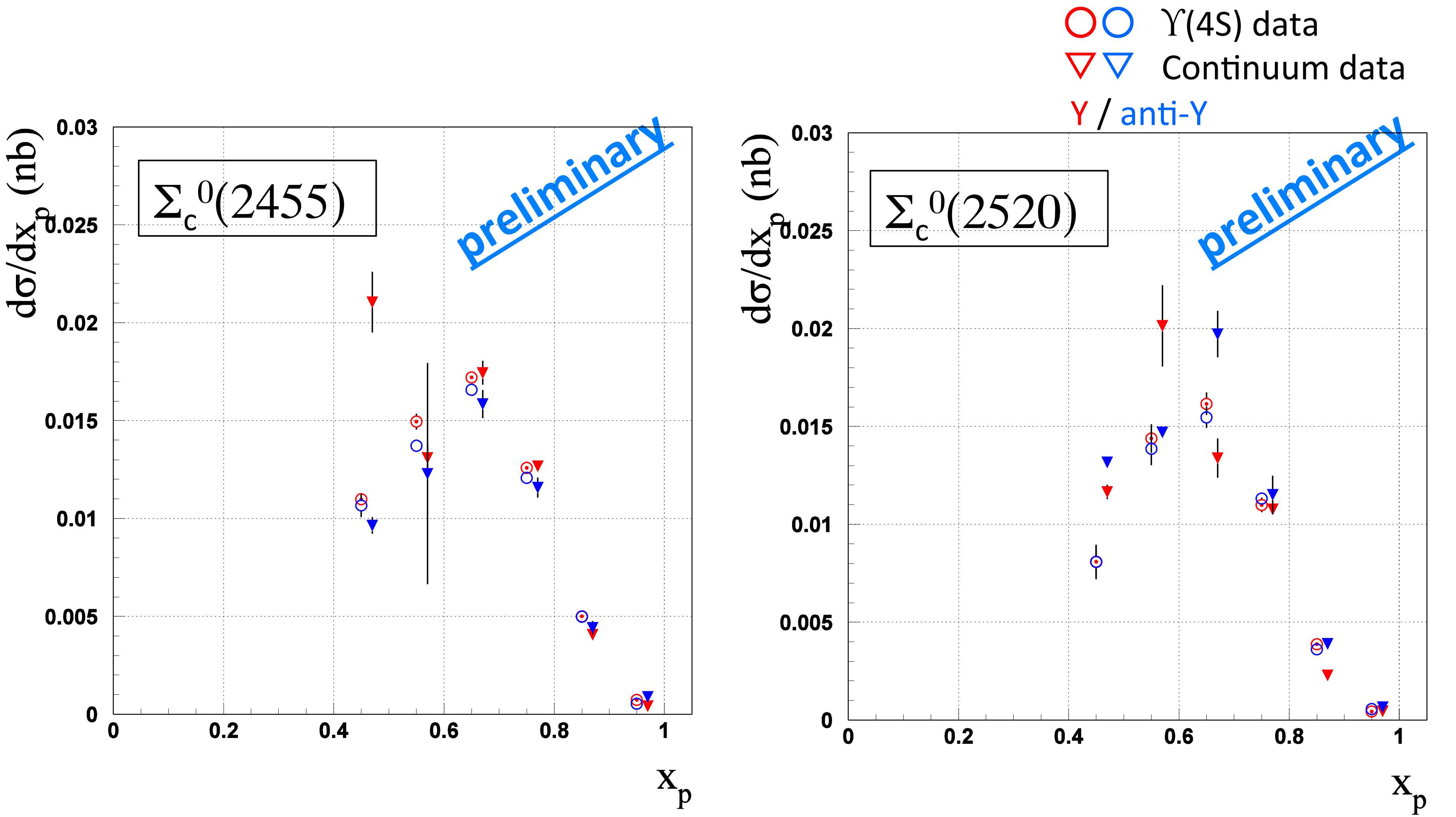
$\Lambda_c^+ \pi^-$ decay processes



Exclude in analysis

- $\Lambda_c^*(2595)^+ \rightarrow \Lambda_c^+ \pi^+ \pi^-$
- $\Lambda_c^*(2625)^+ \rightarrow \Lambda_c^+ \pi^+ \pi^-$

Cross sections of $\Sigma_c(2455)^0$, $\Sigma_c^*(2520)^0$



direct Λ_c and Σ_c production

- Λ_c^+ + c.c. (direct)

$= 189 \pm 66\ pb$ inclusive

$-\ (17.9 \pm 6.0\ pb\ ) \times 3$ $\Sigma_c^{0,+,++}(2455)$ + c.c.

$-\ (18.8 \pm 6.4\ pb) \times 3$ $\Sigma_c^{0,+,++}(2520)$ + c.c.

$-\ (31.3 \pm 10\ pb)$ $\Lambda_c^+(2625)$ + c.c.

$= 47.6 \pm 16.2\ pb$

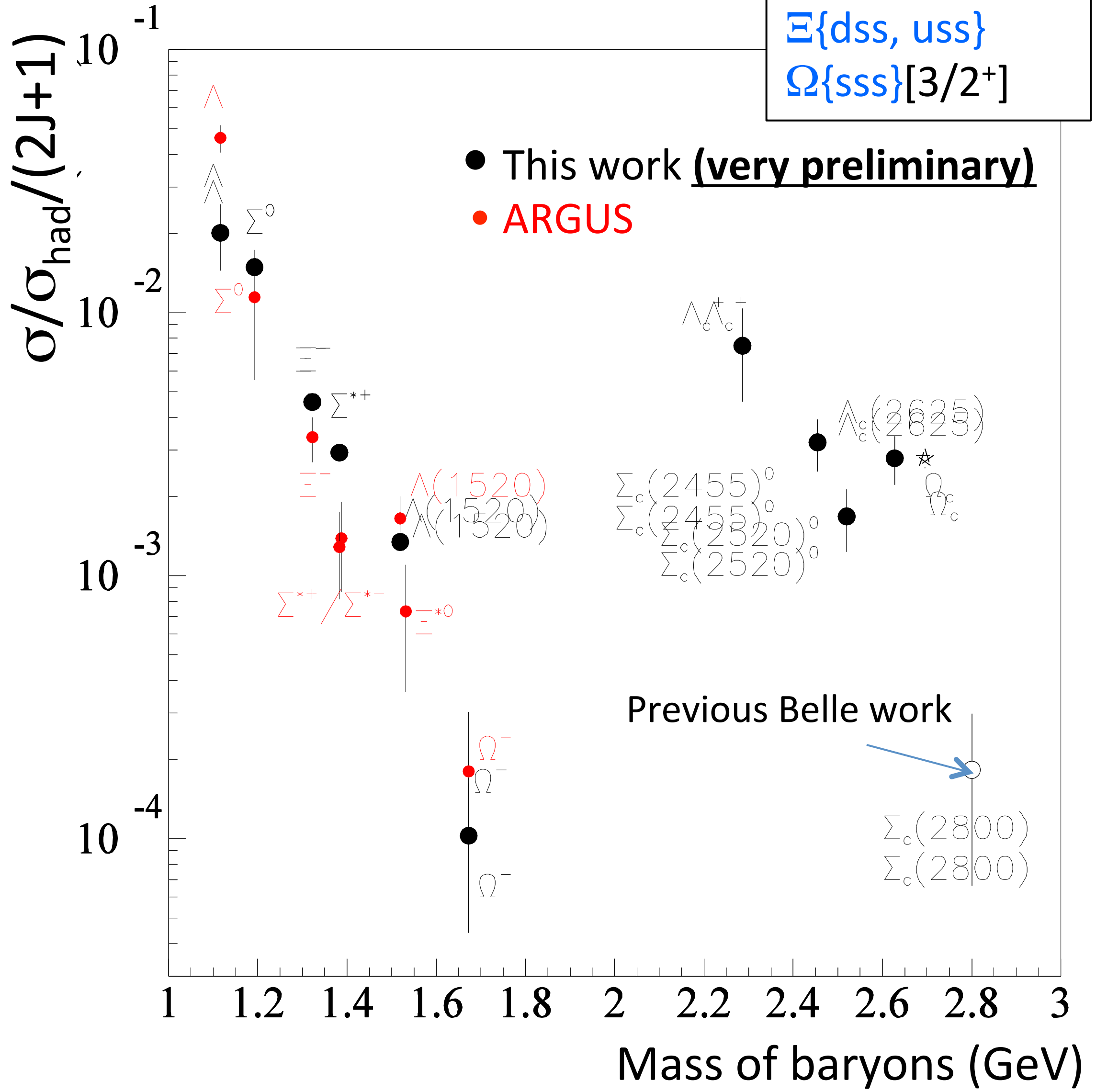
- $\Sigma_c^0(2455)$ +c.c. (direct) = $17.9 \pm 6.0\ pb$
- $\Sigma_c^0(2520)$ + c.c. (direct) = $18.8 \pm 6.4\ pb$
- $\Lambda_c^+(2625)$ + c.c. (direct) = $31.3 \pm 10\ pb$

Λc(2595) and Λc(2775) feed down are included.

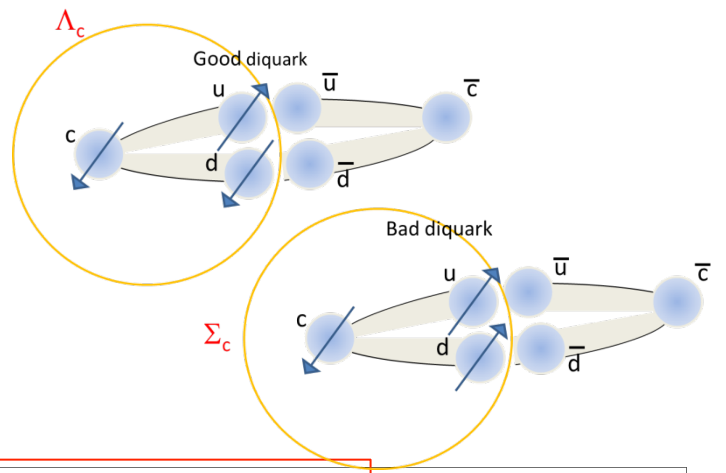
Result and discussion

- Mass dependence
  strange ≠ charm
  not lie on the same line
- Large discrepancy to ARGUS on Λ, and Σ*
  treatment of feed down?
- Deviation of Λ(1520)[3/2⁻] is not clear.
- Ω < Λ, Σ, Ξ
  → Ω[sss] with "↑↑↑"
  no good diquark

Λ{uds}
Λ(1520)[3/2⁻]
Σ{dds,uds,uud}
Σ(1385)[3/2⁺]
Ξ{dss, uss}
Ω{sss}[3/2⁺]

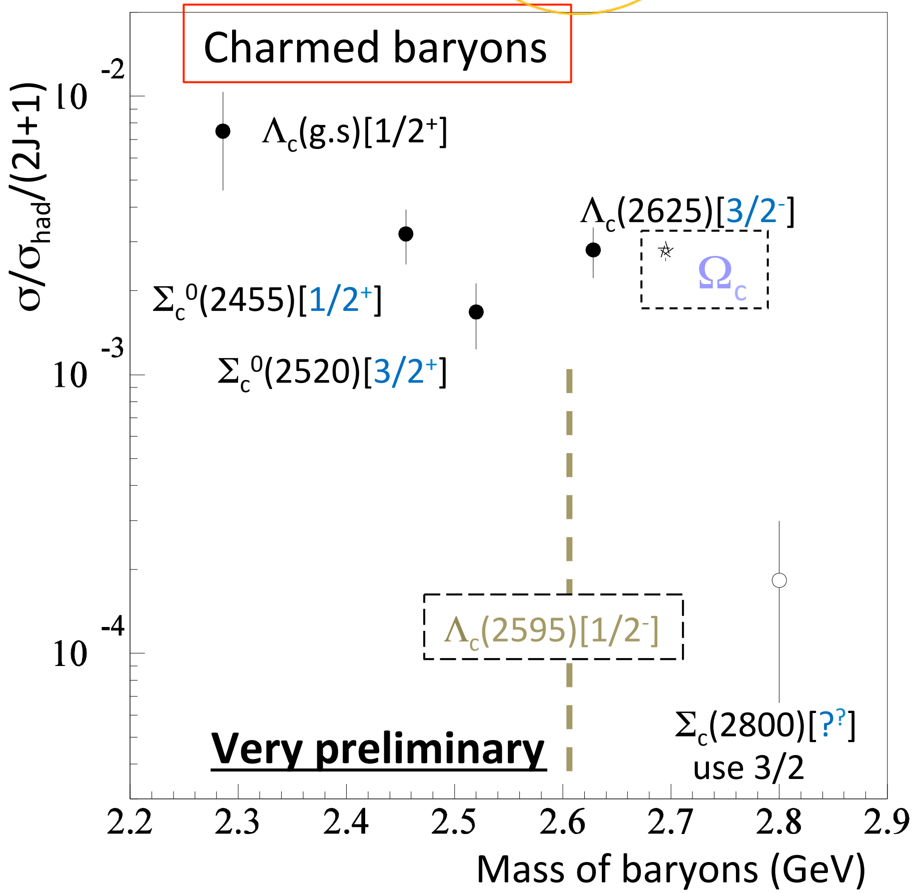


Results and discussion



- Charmed baryons do not lie on "one" line.
  - J^p : no measurement or not well measured
  - quark-model prediction
- $\Lambda_c > \Sigma_c$
  - → good diquark > bad diquark
- Large rate of $\Lambda_c(2625)[3/2^-]$(L=1 state)
  - Prefer [3/2-] or L=1? Why?
  - Rate of $\Lambda(1520)[3/2^-]$ is not large.
  - Rates of $\Lambda_c(2595)[1/2^-]$(L=1 state) and $\Lambda(1405)[1/2-]$ are "key".
- Ωc : no measurement of BR
  - a plot with BR(0.24+-0.12%) by the phenomenological calculation.

Production rate → BR



Summary of NPC result

- We measured production rates R of strange and charmed baryons at $\sqrt{s}$ = 10.52 GeV (continuum data/off-resonance region) in e+e- annihilation at Belle.
- "Systematic" measurement of R provides information on quark structure of hadrons.
- Configuration and performance of Belle detector is good for long-life particles like Λ, Ξ, and Ω.
- We observed 'charmed baryons do not lie on one line'.

  Can we explain by a diquark picture?
- Further study of many baryons with various spin-parity is interesting to see their quark structures.

Heavy Quark Physics

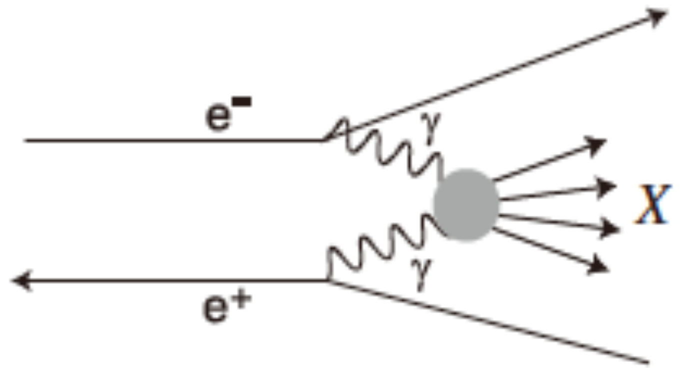
I took most of the results from
J. Brodzicka et. al., PTEP, 2012, 04D001.
Figs. and Tables given hereafter without
explicit ref. are from this paper.

Charmonium Physics

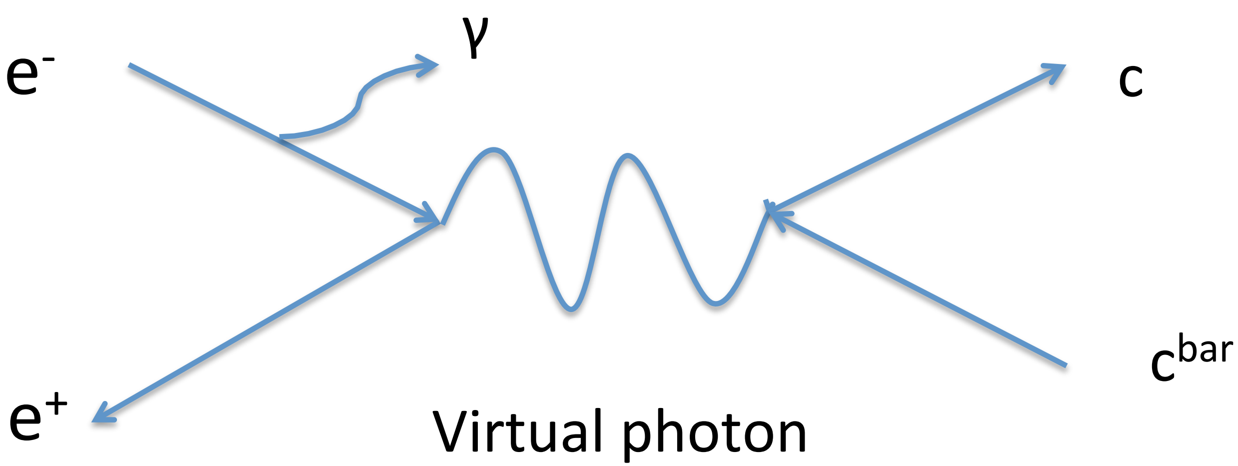
cc^{bar} production mechanisms in e^+e^- collisions at E ~ 10.58 GeV

1. B-meson weak decays
   b -> c c^{bar}s (favored transition)

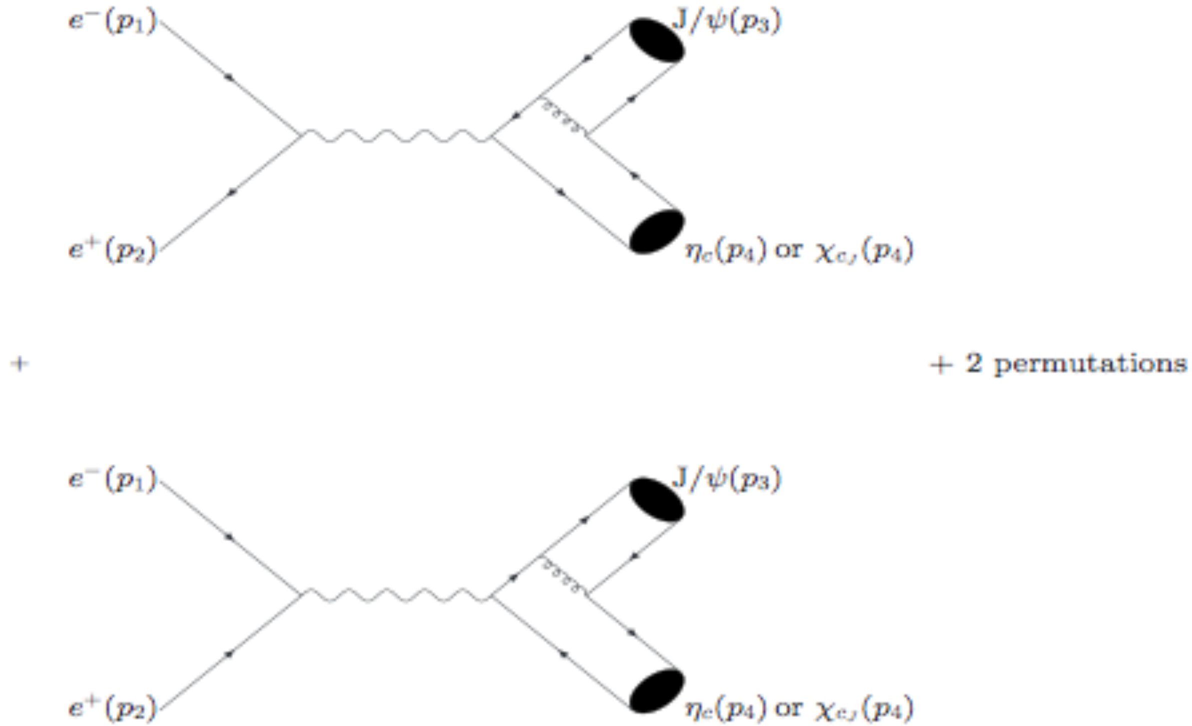
2. γγ fusion: proportional to square of quark charge



3. Near-threshold s-channel cc^{bar} production via initial-state radiation (ISR): 1^{--} state



4. $c\bar{c}$ associated production with J/psi production in $e^- e^+$ annihilation



K. Y. Liu, Z. G. He, and K. T. Chao, Phys. Lett. B 557 (2003) 45, arXiv:hep-ph/0211181

Figure 1: Feynman diagrams for $e^+e^- \to J/\psi + \eta_c(\chi_{cJ})$.

$$\eta_c(2S)$$

$$B \to K\eta_c(2S)$$

$$\eta_c(2S) \to K_S\, K^{\pm}\, \pi^{\mp}$$

$$e^+ e^- \to J/\psi\, X$$

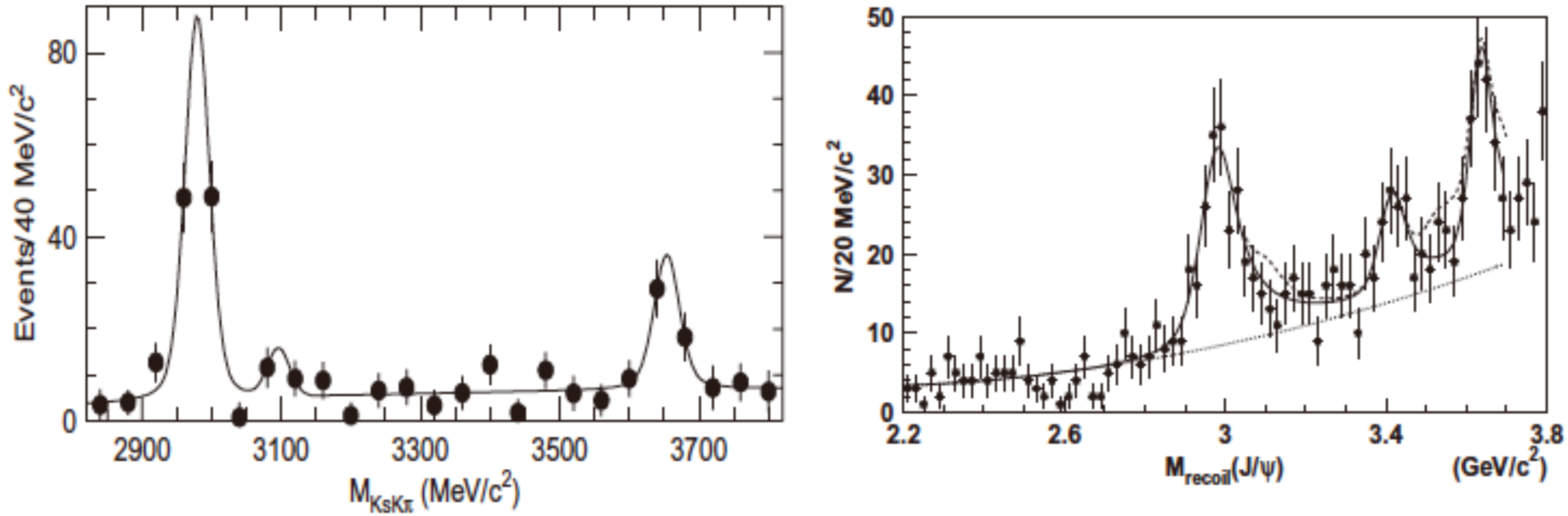


Fig. 61. Left: The $K_S K^{\pm}\pi^{\mp}$ mass distribution from $B \to K K_S K^{\pm}\pi^{\mp}$ decays [307]. The large peak on the left is the η_c; the smaller peaks on the right are the J/psi (around 3.1 GeV) and $\eta_c(2S)$ signals. Right: The J/ψ recoil mass spectrum in inclusive $e^+e^- \to J/\psi\ X$ processes [308]. A fit with η_c, χ_{c0}, and $\eta_c(2S)$ contributions is shown as a solid curve. The dashed curve in the figure corresponds to the case where the contributions of the J/ψ, χ_{c1}, χ_{c2}, and $\psi(2S)$ are set at their 90% C.L. upper limit values. The dotted curve is the background function.

Belle Collaboration / Physics Letters B 706 (2011) 139–149

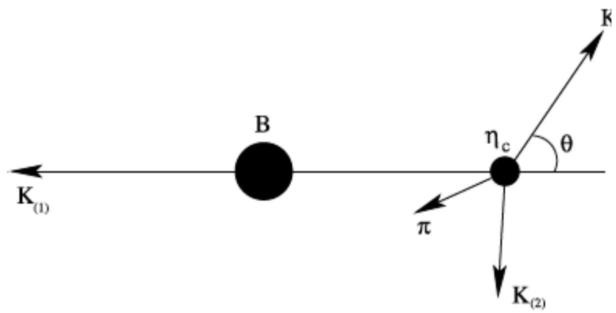


Fig. 3. The decay $B^{\pm} \to K^{\pm}\eta_c \to K^{\pm}(K_S K\pi)^0$.

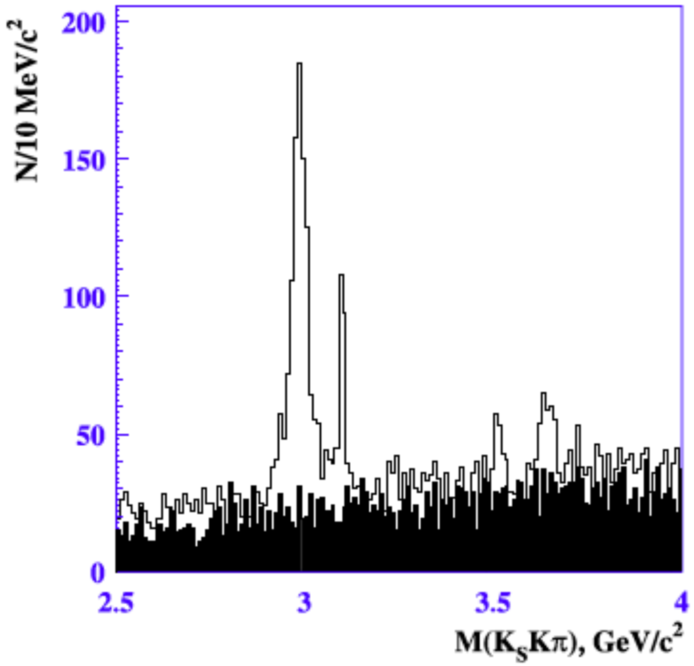


Fig. 4. The signal distribution of $(K_S K^{\pm}\pi^{\mp})$ invariant mass in the $B^{\pm} \to K^{\pm}(K_S K\pi)^0$ decay. The charmonium states η_c, J/ψ, χ_{c1}, and $\eta_c(2S)$ (in order of mass) can be seen. The solid histogram is the combinatorial background determined from the ΔE sideband region.

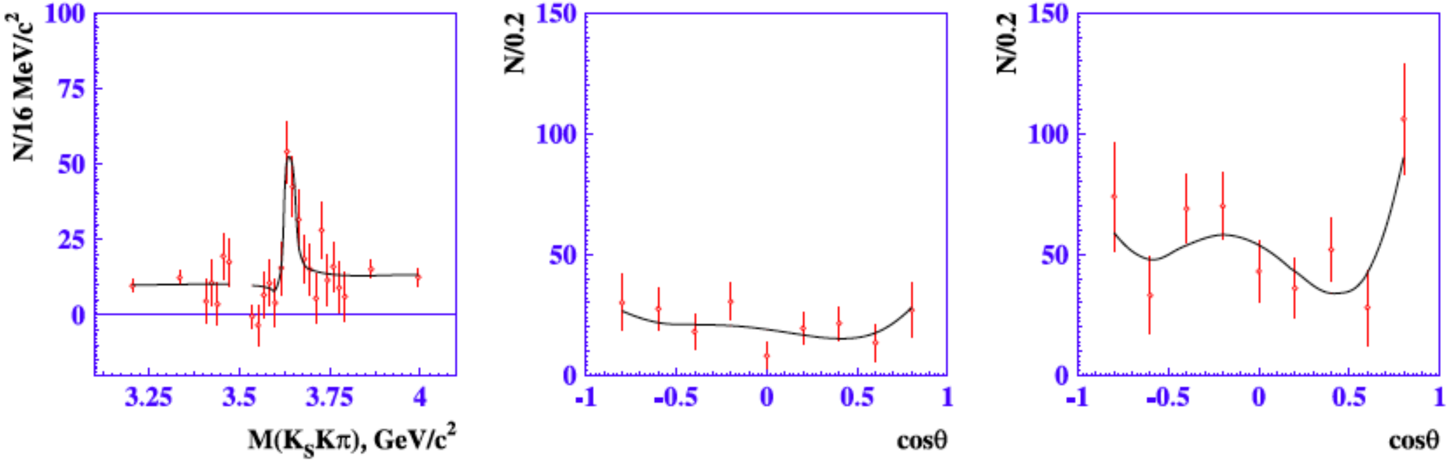


Fig. 10. Projections of the fit in $K_S K \pi$ invariant mass in the $\eta_c(2S)$ mass region (left) and $\cos\theta$ in the $\eta_c(2S)$ invariant mass signal (center) and sideband (right) regions. The combinatorial background is subtracted. The gap near 3.5 GeV/c^2 is due to the χ_{c1} veto. The bin size along the $\cos\theta$ axis is 0.2. Along the $M(K_S K\pi)$ axis the bin size is 16 MeV/c^2 in the signal region and 130 MeV/c^2 in the sideband region.

Table 5
Comparison of the results obtained under the assumption of no interference between the signal and the non-resonant contribution and those obtained with interference.

	No interference	Taking interference into account
$B^{\pm} \to K^{\pm}\eta_c$, $\eta_c \to (K_S K\pi)^0$		
$\mathcal{B} \times \mathcal{B}$, 10^{-6}	$24.0 \pm 1.2(stat)^{+2.1}_{-2.0}(syst)$	$26.7 \pm 1.4(stat)^{+2.9}_{-2.6}(syst) \pm 4.9(model)$
Mass, MeV/c^2	$2984.8 \pm 1.0(stat)^{+0.1}_{-2.0}(syst)$	$2985.4 \pm 1.5(stat)^{+0.5}_{-2.0}(syst)$
Width, MeV/c^2	$35.4 \pm 3.6(stat)^{+3.0}_{-2.1}(syst)$	$35.1 \pm 3.1(stat)^{+1.0}_{-1.6}(syst)$
$B^{\pm} \to K^{\pm}\eta_c(2S)$, $\eta_c(2S) \to (K_S K\pi)^0$		
$\mathcal{B} \times \mathcal{B}$, 10^{-6}	$3.1 \pm 0.8(stat) \pm 0.2(syst)$	$3.4^{+2.2}_{-1.5}(stat + model)^{+0.5}_{-0.4}(syst)$
Mass, MeV/c^2	$3646.5 \pm 3.7(stat)^{+1.2}_{-2.9}(syst)$	$3636.1^{+3.9}_{-4.2}(stat + model)^{+0.7}_{-2.0}(syst)$
Width, MeV/c^2	$41.1 \pm 12.0(stat)^{+6.4}_{-10.9}(syst)$	$6.6^{+8.4}_{-5.1}(stat + model)^{+2.6}_{-0.9}(syst)$

Lessons we have learned from eta(2S) analyses

- Belle can observe the state in not only one mode but also other modes.
- Belle can study angler distribution of decaying objects to study spin of the state.
- Careful analyses improve the results (such as interference effect)

$$Z_c(3900)^{\pm}$$

$Z_c(3900)$ at Belle

- Reference: PRL 110, 252002 (2013)

$e^+e^- \rightarrow \gamma(ISR)\pi^+\pi^- J/\psi$ Y(4260) 1^{--}

$$Y(4260) \rightarrow \pi^+\pi^- J/\psi$$

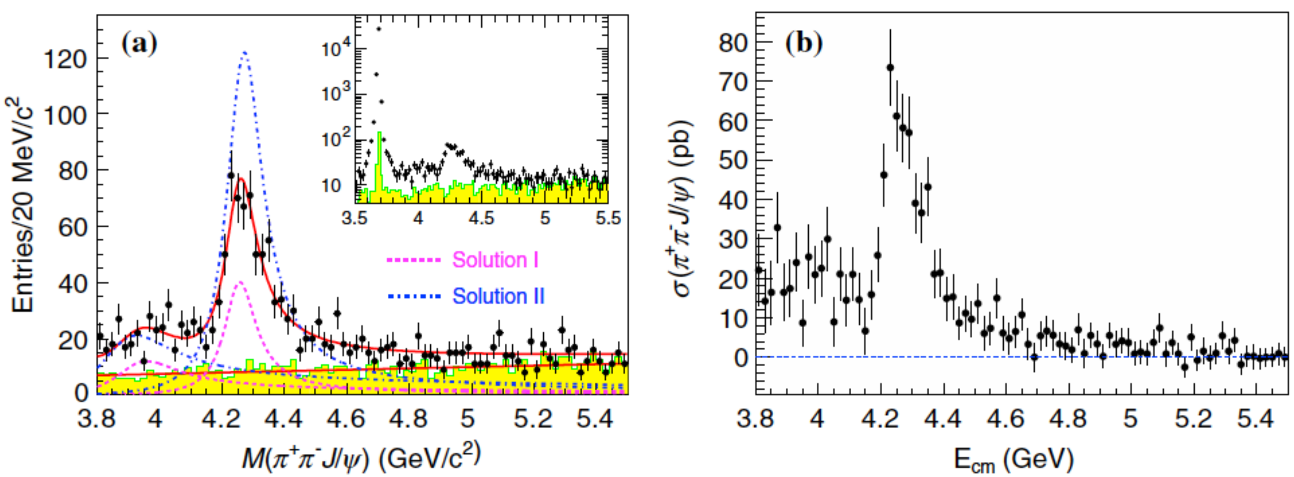


FIG. 1 (color online). (a) Invariant mass distributions of $\pi^+\pi^-\ell^+\ell^-$. Points with error bars are data, and the shaded histograms are the normalized J/ψ mass sidebands. The solid curves show the total best fit with two coherent resonances and contribution from background. The dashed curves are for solution I, while the dotted-dashed curves are for solution II. The inset shows the distributions on a logarithmic vertical scale. The large peak around 3.686 GeV$/c^2$ is the $\psi(2S) \to \pi^+\pi^- J/\psi$ signal. (b) Cross section of $e^+e^- \to \pi^+\pi^- J/\psi$ after background subtraction. The errors are statistical only.

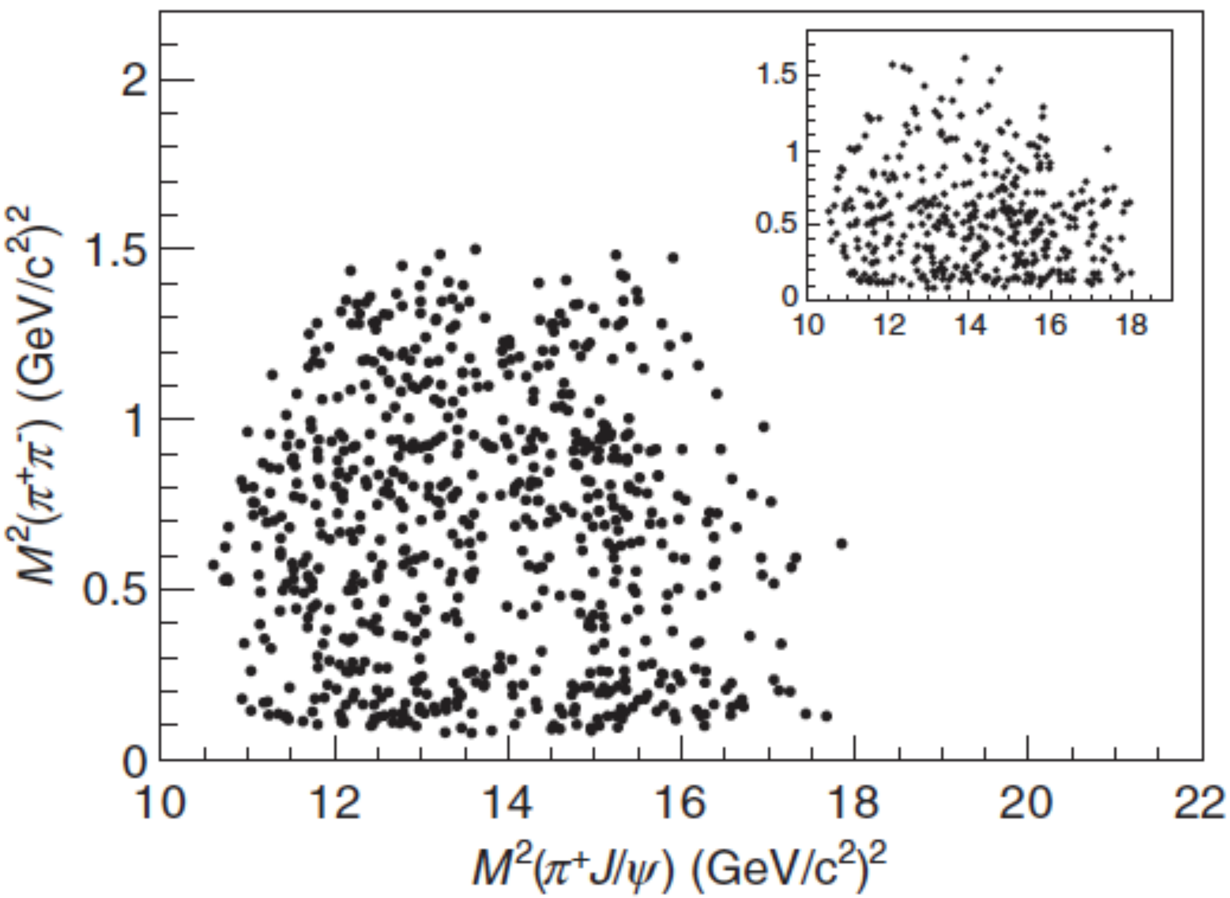


FIG. 2. Dalitz plot for $Y(4260) \to \pi^+\pi^- J/\psi$ decays for $4.15\ \mathrm{GeV}/c^2 < M(\pi^+\pi^- J/\psi) < 4.45\ \mathrm{GeV}/c^2$. The inset shows background events from the J/ψ-mass sidebands (not normalized).

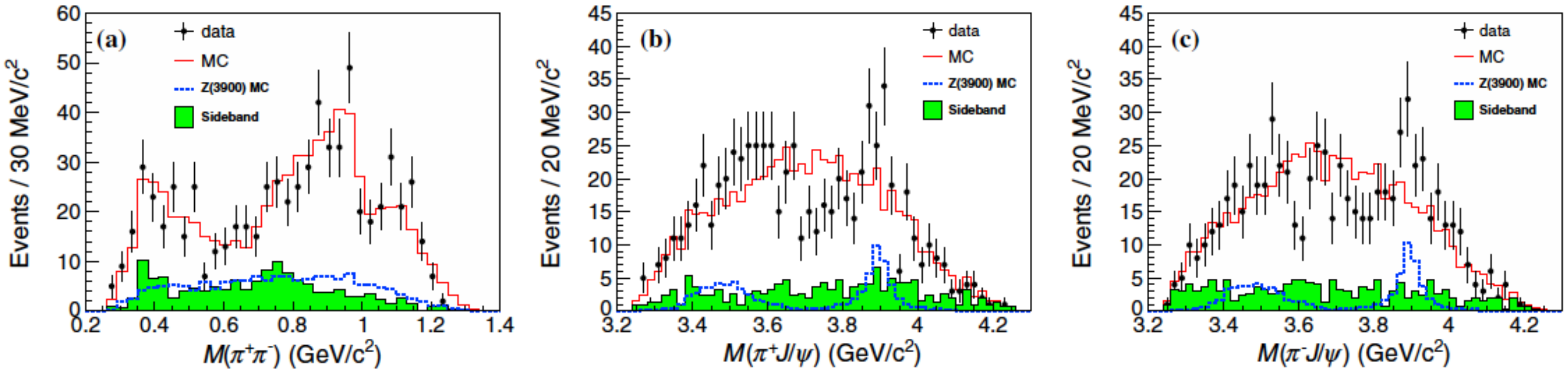


FIG. 3 (color online). Invariant mass distributions of (a) $\pi^+\pi^-$, (b) π^+J/ψ, and (c) π^-J/ψ for events in the $Y(4260)$ signal region. Points with error bars represent data, shaded histograms are normalized background estimates from the J/ψ-mass sidebands, solid histograms represent MC simulations of $\pi^+\pi^-$ amplitudes [22] (normalized J/ψ-mass sideband events added) and dashed histograms are MC simulation results for a $Z(3900)^\pm$ signal.

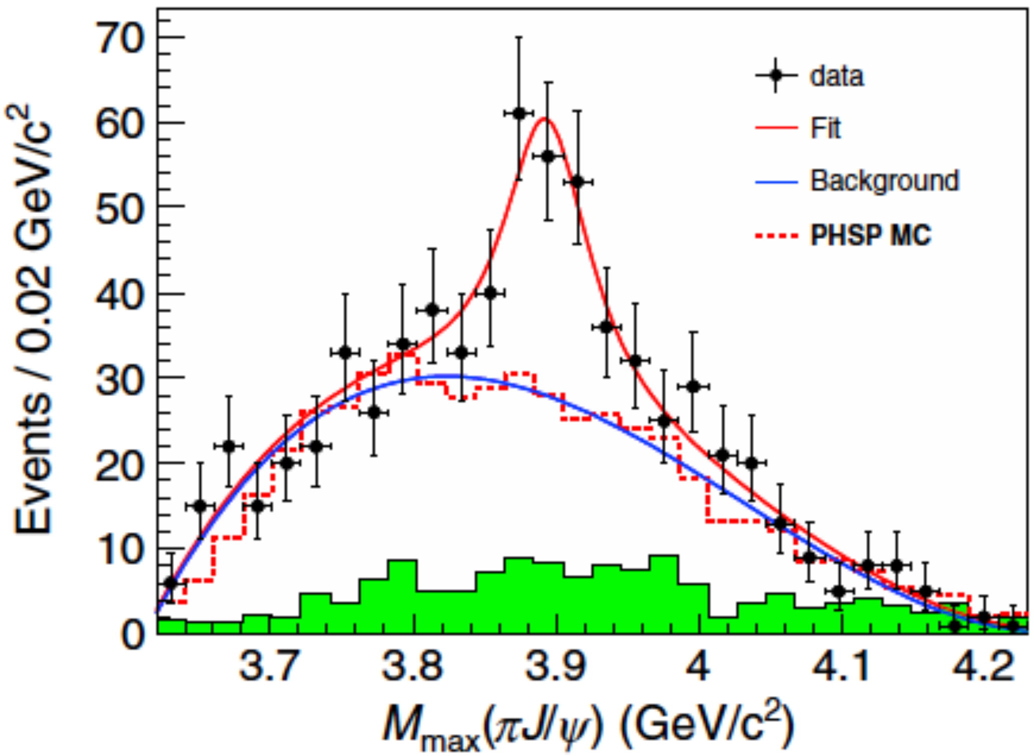


FIG. 4 (color online). Unbinned maximum likelihood fit to the distribution of the $M_{\rm max}(\pi J/\psi)$. Points with error bars are data, the curves are the best fit, the dashed histogram is the phase space (PHSP) distribution and the shaded histogram is the non-$\pi^+\pi^- J/\psi$ background estimated from the normalized J/ψ sidebands.

$Z_c(3900)$ at Belle

- Mass: (3894.5±6.6±4.5) MeV
- Width: (63±24±26) MeV
- Consistent with Belle result

Z_c(3900) at BESIII

- Reference: PRL 110, 252001 (2013)

$$e^+e^- \rightarrow \pi^+\pi^- J/\psi$$ at E = 4.26 GeV

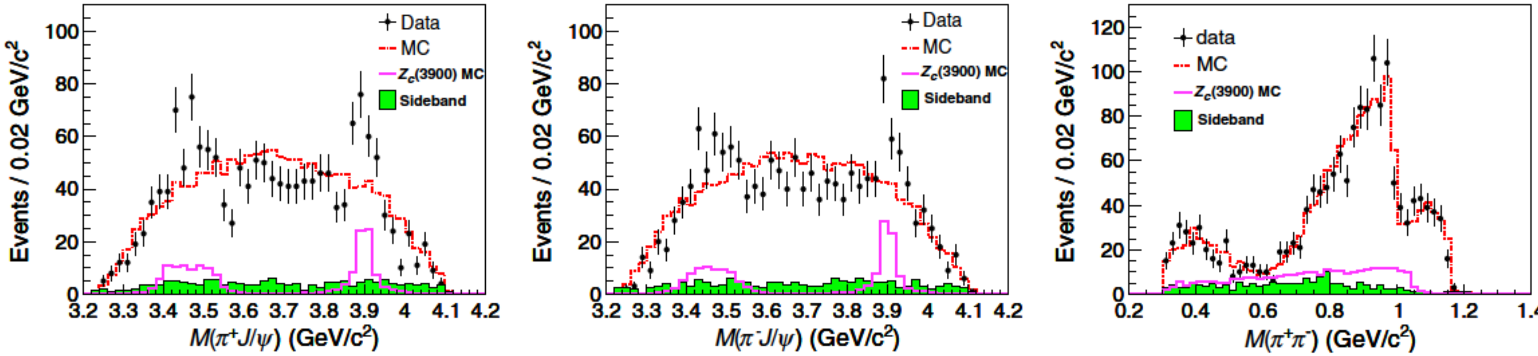


FIG. 3 (color online). One dimensional projections of the $M(\pi^+ J/\psi)$, $M(\pi^- J/\psi)$, and $M(\pi^+\pi^-)$ invariant mass distributions in $e^+e^- \to \pi^+\pi^- J/\psi$ for data in the J/ψ signal region (dots with error bars), data in the J/ψ sideband region (shaded histograms), and MC simulation results from $\sigma(500)$, $f_0(980)$, and nonresonant $\pi^+\pi^-$ amplitudes (red dotted-dashed histograms). The pink blank histograms show a MC simulation of the $Z_c(3900)$ signal with arbitrary normalization.

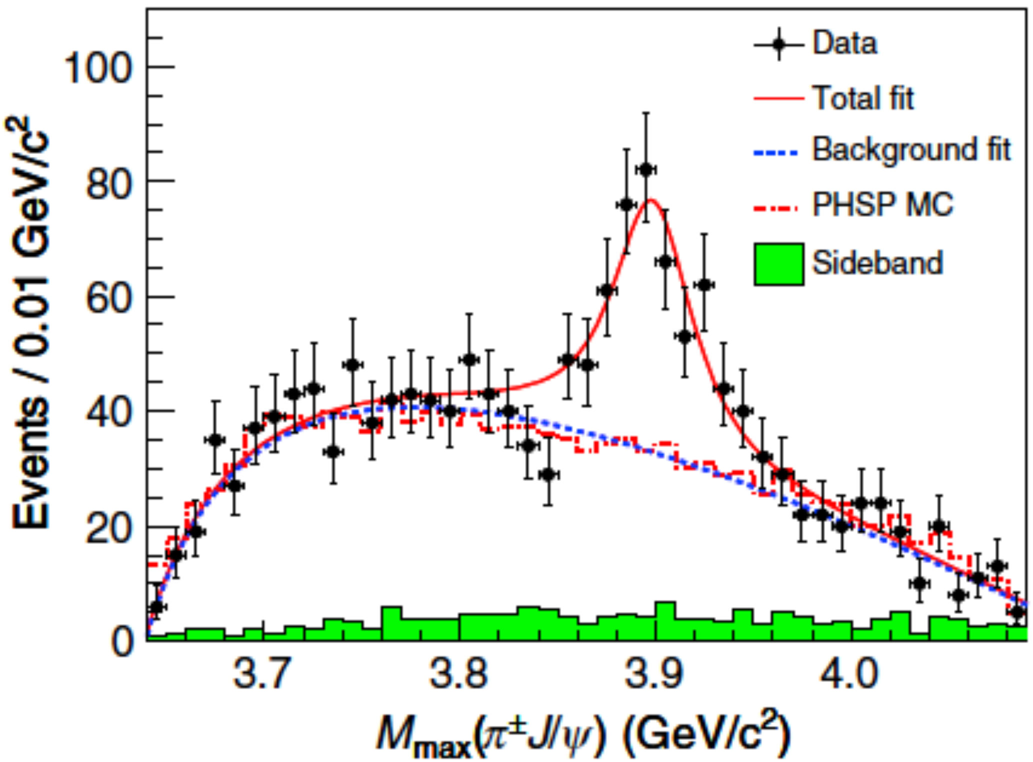


FIG. 4 (color online). Fit to the $M_{\max}(\pi^{\pm}J/\psi)$ distribution as described in the text. Dots with error bars are data; the red solid curve shows the total fit, and the blue dotted curve the background from the fit; the red dotted-dashed histogram shows the result of a phase space (PHSP) MC simulation; and the green shaded histogram shows the normalized J/ψ sideband events.

$Z_c(3900)$ at BESIII

- Mass: $(3899.0 \pm 3.6 \pm 4.9)$ MeV
- Width: $(46 \pm 10 \pm 20)$ MeV
- Statistical significance > 5.2σ

$D^0 D^{*-}$ threshold: 3875.15 MeV

X(3940)

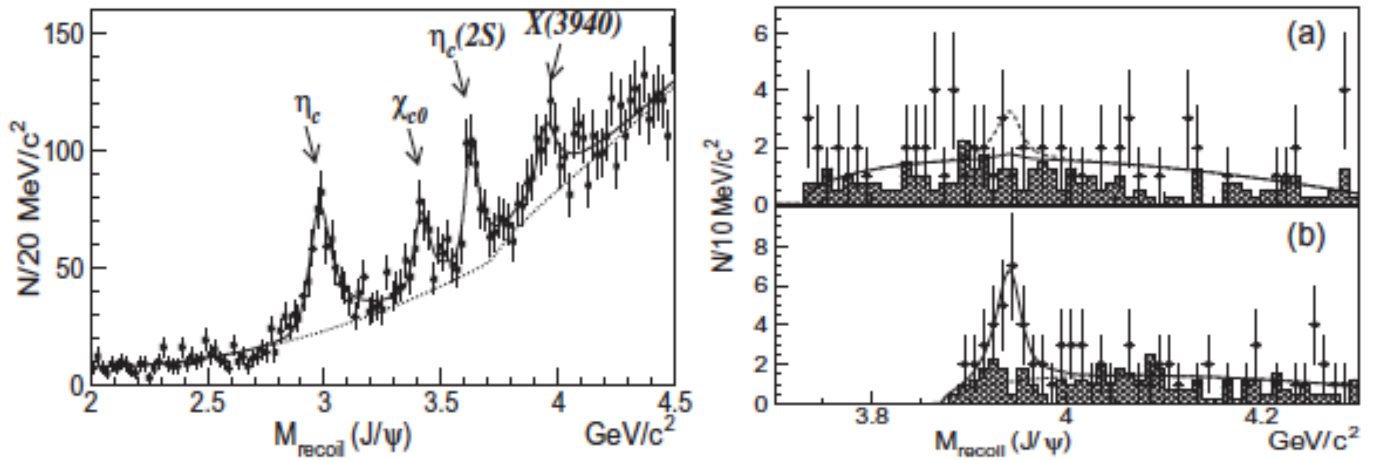


Fig. 65. Left: The distribution of masses recoiling from the J/ψ in inclusive $e^+e^- \to J/\psi\, X$ reactions [334]. The solid curve shows the result of a fit that includes η_c, χ_{c0}, $\eta_c(2S)$, and $X(3940)$ resonance terms as well as a smooth background function that has a step at the $D\bar{D}$ threshold (dotted curve). Right: The a) $D\bar{D}$ and b) $D^*\bar{D}$ invariant mass distributions from exclusive $e^+e^- \to J/\psi\, D^{(*)}\bar{D}$ annihilation [334]. The curves are fits that include possible resonance terms and the histograms are backgrounds determined from the D-meson sidebands. The dashed curves show: a) the 90% C.L. upper limit on the signal; b) the background function.

Is X(3940) η(3S)?

- Decay pattern is OK?

- Ψ(3S) is the spin triplet partner of η(3S)
  Mass: (4040±4) MeV

  Hyper fine splitting is about 98 MeV
  which is twice as large as that of 2S states
  too large!

TABLE 43: Experimental measurements and NRQCD predictions for $e^+e^- \to J/\psi + H$, where H is η_c, χ_{c0}, or $\eta_c(2S)$. Cross sections are in units of fb. The quantity $\mathcal{B}_{>2}$ is the branching fraction of the charmonium state that is recoiling against the J/ψ into more than two charged tracks

Quantity	$\eta_c(1S)$	$\chi_{c0}(1P)$	$\eta_c(2S)$
$\sigma \times \mathcal{B}_{>2}$ (Belle [782])	$25.6 \pm 2.8 \pm 3.4$	$6.4 \pm 1.7 \pm 1.0$	$16.5 \pm 3.0 \pm 2.4$
$\sigma \times \mathcal{B}_{>2}$ (*BABAR* [53])	$17.6 \pm 2.8^{+1.5}_{-2.1}$	$10.3 \pm 2.5^{+1.4}_{-1.8}$	$16.4 \pm 3.7^{+2.4}_{-3.0}$
σ (Liu, He, Chao [779])	5.5	6.9	3.7
σ (Braaten, Lee [780])	3.78 ± 1.26	2.40 ± 1.02	1.57 ± 0.52
σ (Hagiwara, Kou, Qiao [781])	2.3		
σ (Bodwin *et al.* [783])	17.5 ± 5.7		
σ (He, Fan, Chao [784])	20.4		
σ (Bodwin, Lee, Yu [785])	$17.6^{+8.1}_{-6.7}$		

N. Brambilla et al. (Quarkonium Working Group), Eur. Phys. J. C 71, 1534 (2011).

$c\bar{c}$ $c\bar{c}$ production rate

- Large J/psi η_c production rate
- How about the production rate of the double charm baryon?
- Theoretical estimation is desirable!

Bottomonium physics

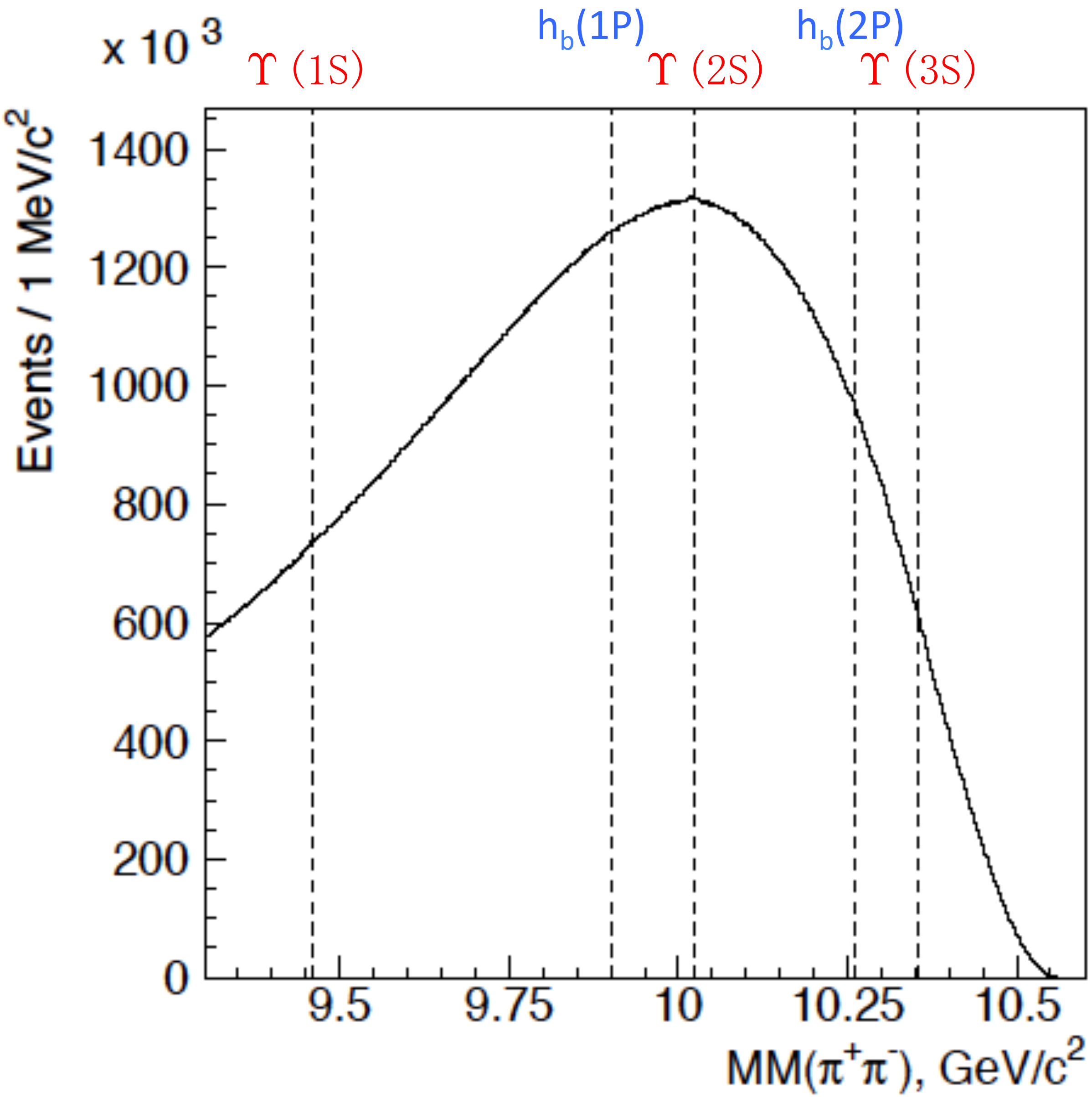
$h_b(1P)$ and $h_b(2P)$

- Reference: Phys. Rev. Lett. 108, 032001 (2012).
  e^+e^- -> $\Upsilon(5S)$ -> $h_b(nP)\pi^+ \pi^-$

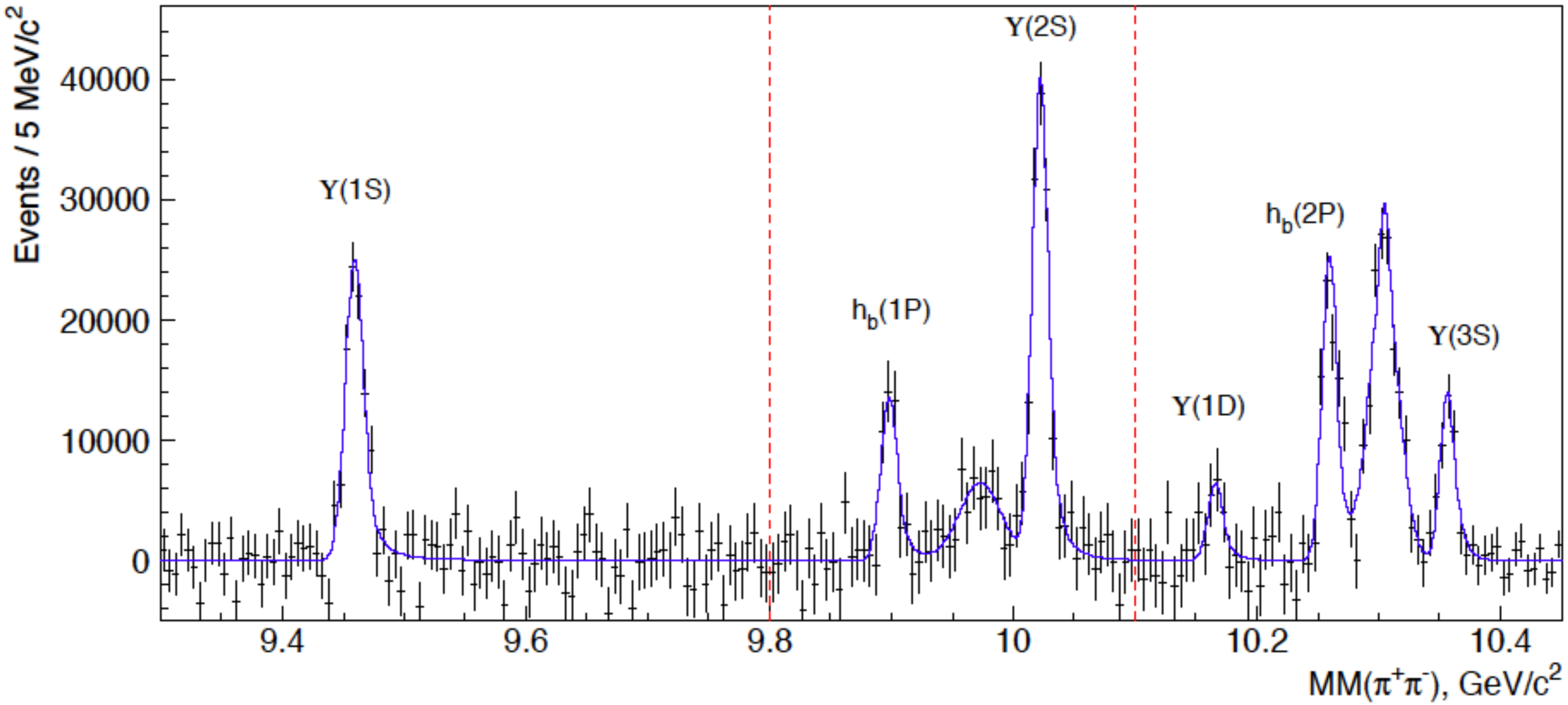
- $b b^{bar}$: S=0, L=1, $J^{PC} = 1^{+-}$
- $M(h_b(1P)) = 9898.25 \pm 1.06\ ^{+1.03}_{-1.07}$ MeV/c^2
  significance 5.5σ
- $M(h_b(2P)) = 10259.76 \pm 0.64\ ^{+1.43}_{-1.03}$ MeV/c^2
  significance 11.2σ

- Missing mass spectrum of π⁺ π⁻

$$MM(\pi^+\pi^-) \equiv \sqrt{(E_{c.m.} - E^*_{\pi^+\pi^-})^2 - p^{*2}_{\pi^+\pi^-}},$$



x 10 3
Υ (1S)
$h_b(1P)$
Υ (2S)
$h_b(2P)$
Υ (3S)
Events / 1 MeV/c²
1400
1200
1000
800
600
400
200
0
9.5
9.75
10
10.25
10.5
MM(π⁺π⁻), GeV/c²



Missing Mass ($\pi^+\pi^-$) spectrum with combinatorial background and K^0_S contributions subtracted

$Z_b^{\pm}(10610)$ and $Z_b^{\pm}(10650)$

- Phys. Rev. Lett. 108, 122001 (2012).

$e^+e^- \to \Upsilon(5S) \to Z_b^{-+} \; \pi^{+-}$

- Charged bottom like mesons -> explicitly exotic
- $M(Z_{b,1})$ = 10608.4 ± 2.0 MeV/c^2

  Γ_1 = 15.6 ± 2.5 MeV

  $B\bar{B}^{*}$ (BB^{*bar}) threshold: 10604 MeV/c^2

- $M(Z_{b,2})$ = 10653.2 ± 1.5 MeV/c^2

  Γ_2 = 14.4 ± 3.2 MeV

  B^*B^{*bar} threshold: 10650 MeV/c^2

- $I^G(J^P) = 1^+(1^+)$

Analysis of $\Upsilon(5S) \to \Upsilon(1S, 2S, 3S)\pi^+\pi^-$

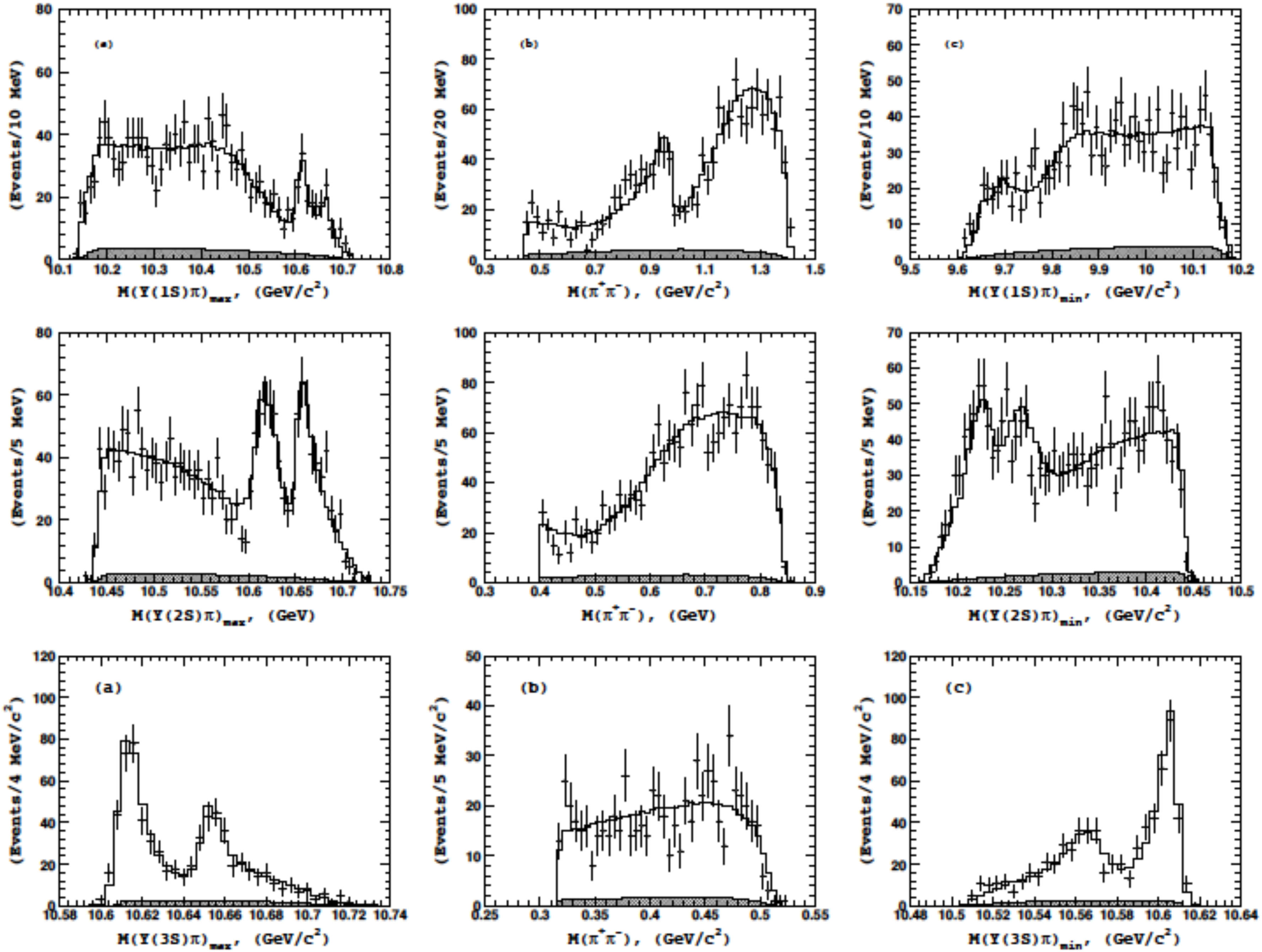
- Three-body decay amplitude

$$M(s_1, s_2) = A_1(s_1, s_2) + A_2(s_1, s_2) + A_{f0} + A_{f_2} + A_{NR},$$

$$s_1 = M^2(\Upsilon(nS)\pi^+),\ s_2 = M^2(\Upsilon(nS)\pi^-).$$

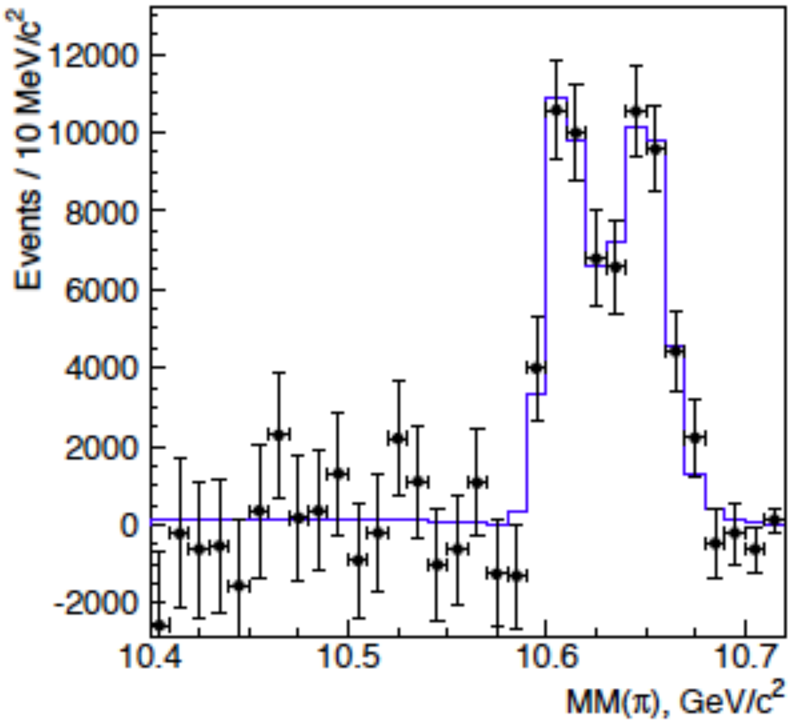
$$A_k(s_1, s_2) = a_k e^{i\delta_k}(BW(s_1, M_k, \Gamma_k) + BW(s_2, M_k, \Gamma_k)),$$

2 Z_b resonances and $f_0(980)$, $f_2(1270)$ contributions are included in the amplitude

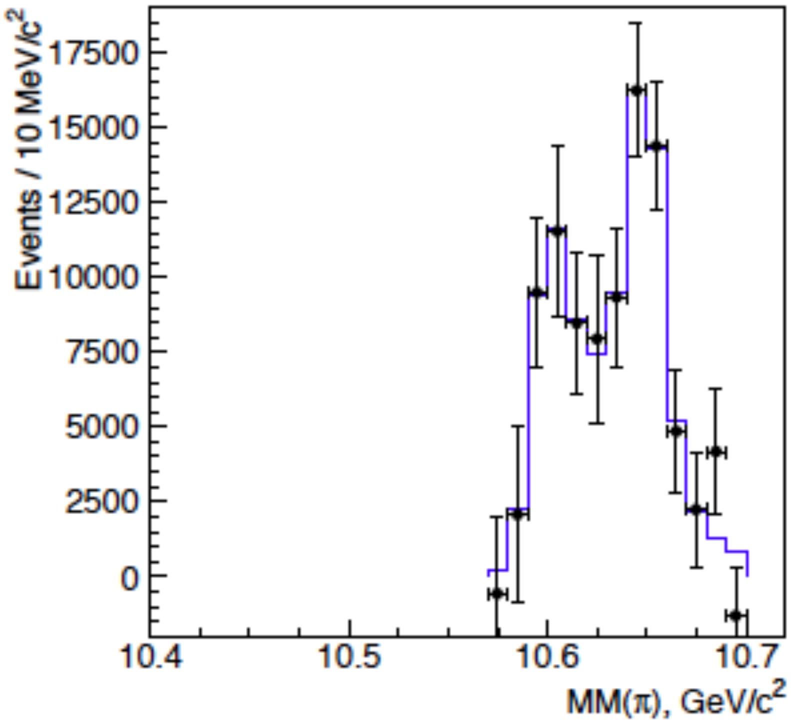


(a)
(b)
(c)
(Events/10 MeV)
(Events/20 MeV)
(Events/10 MeV)
M(Υ(1S)π)max, (GeV/c2)
M(π+π−), (GeV/c2)
M(Υ(1S)π)min, (GeV/c2)
(Events/5 MeV)
(Events/5 MeV)
(Events/5 MeV)
M(Υ(2S)π)max, (GeV)
M(π+π−), (GeV)
M(Υ(2S)π)min, (GeV/c2)
(a)
(b)
(c)
(Events/4 MeV/c2)
(Events/5 MeV/c2)
(Events/4 MeV/c2)
M(Υ(3S)π)max, (GeV/c2)
M(π+π−), (GeV/c2)
M(Υ(3S)π)min, (GeV/c2)

Analysis of $\Upsilon(5S) \to h_b(1P, 2P)\pi^+\pi^-$



$h_b(1P)$



$h_b(2P)$

$Z_b^0(10610)$

- Phys. Rev. D 88, 052016 (2013)
- Dalitz analysis of $\Upsilon(10860) \to \Upsilon(2,3S)\pi^0\pi^0$

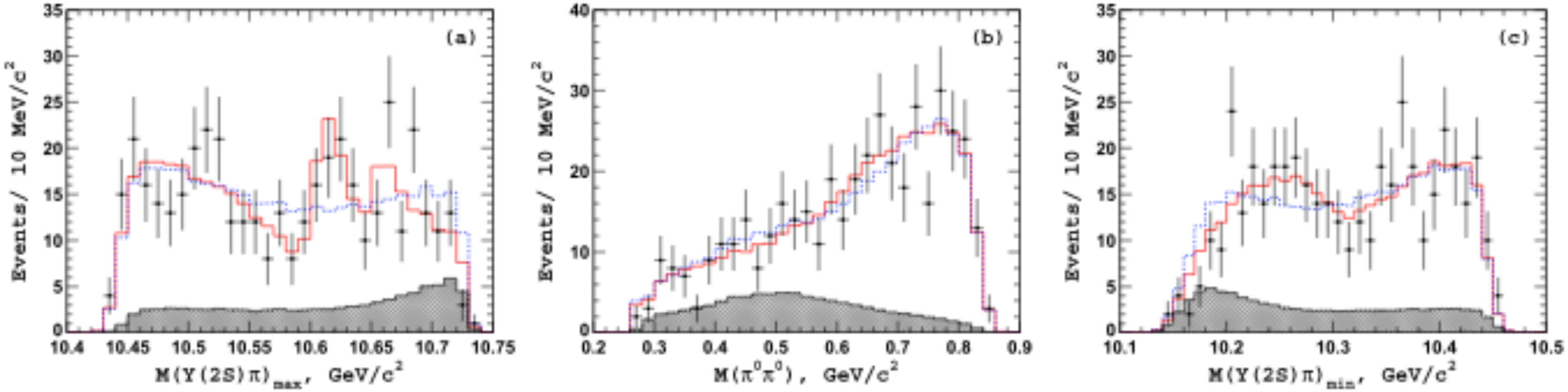


FIG. 4 (color online). Comparison of the (a) $M(\Upsilon(2S)\pi^0)_{\rm max}$, (b) $M(\pi^0\pi^0)$, and (c) $M(\Upsilon(2S)\pi^0)_{\rm min}$ distributions for the $\Upsilon(2S)\pi^0\pi^0$ events in the signal region (points with error bars) and results of the fit (open histograms). The legends are the same as in Fig. 3. Only solution A is shown. Both solutions give indistinguishable plots.

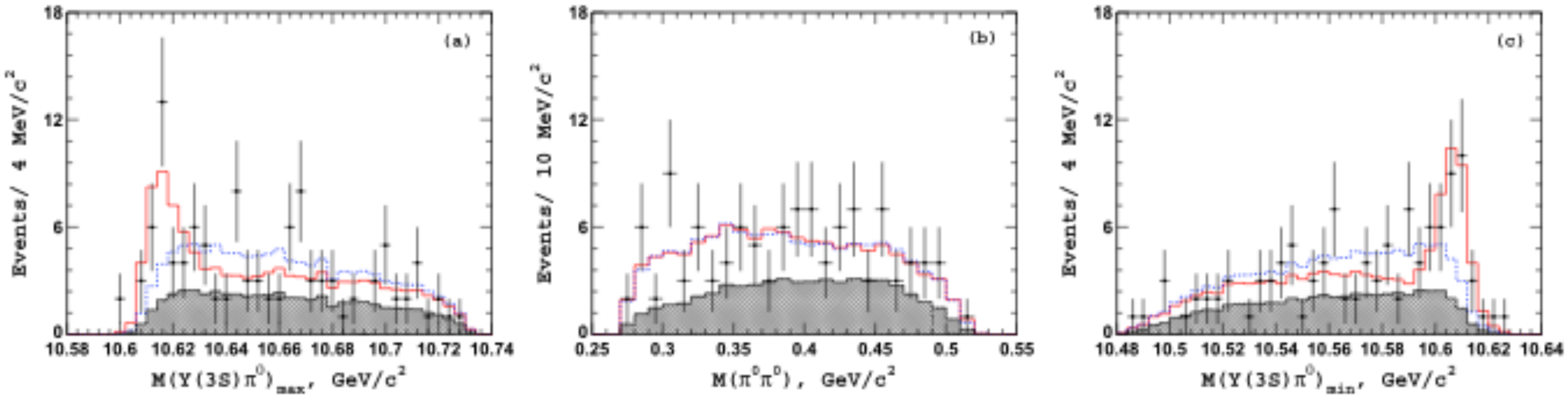


FIG. 5 (color online). Comparison of the (a) $M(\Upsilon(3S)\pi^0)_{\rm max}$, (b) $M(\pi^0\pi^0)$, and (c) $M(\Upsilon(3S)\pi^0)_{\rm min}$ distributions for the $\Upsilon(3S)\pi^0\pi^0$ events in the signal region (points with error bars) and results of the fit (open histograms). The legends are the same as in Fig. 3.

$Z_b^0(10610)$

- Mass: (10609±4±4) MeV
- Statistical significance is 6.5σ
- $Z_b^0(10650)$ signal is not significant.

Charmed baryons

$\Lambda_c(2880)$

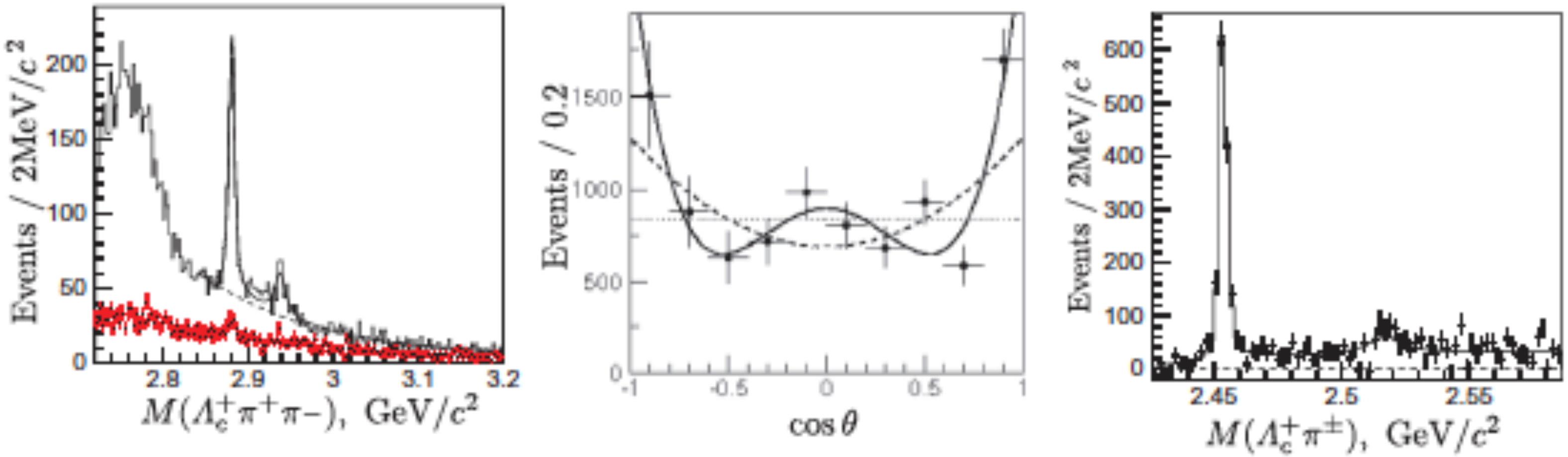


Fig. 77. Left: $M(\Lambda_c^+\pi^+\pi^-)$ distribution with $\Lambda_c^+\pi^\pm$ within $\Sigma_c(2455)^{0,++}$ signal (black) and sideband (red) regions. Middle: Helicity distribution of $\Lambda_c(2880) \to \Sigma_c(2455)\pi$ with fit results for the $J = \frac{1}{2}$ (dotted), $\frac{3}{2}$ (dashed), and $\frac{5}{2}$ (solid) hypotheses. Right: $\Lambda_c(2880)$ yield as a function of $M(\Lambda_c^+\pi^\pm)$.

$\Sigma_c(2800)$

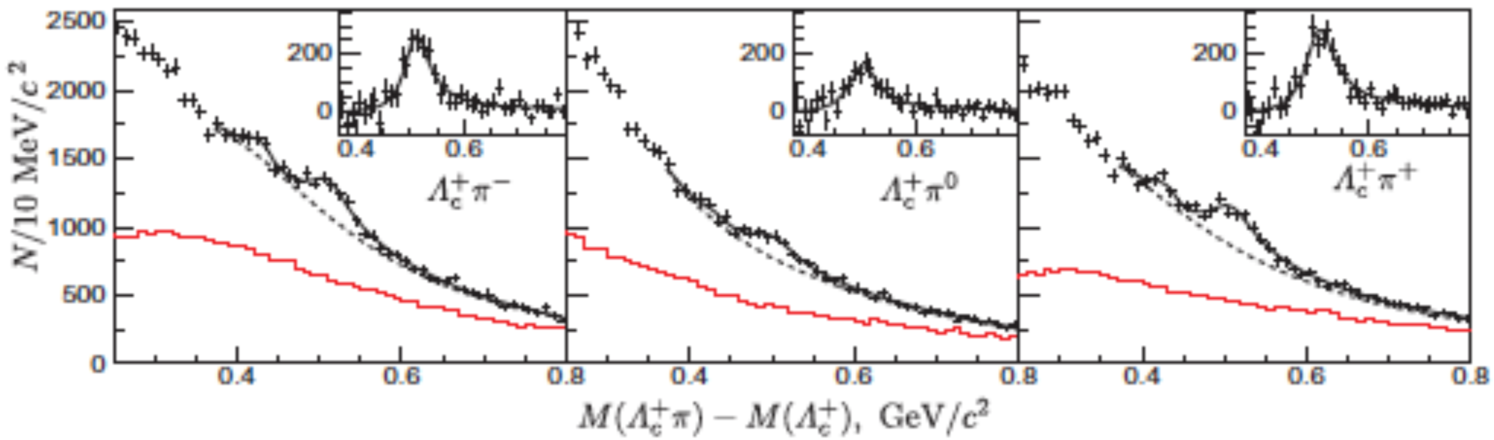


Fig. 78. $M(\Lambda_c\pi) - M(\Lambda_c)$ distributions for the Λ_c^+ signal window (points) and scaled sidebands (red histogram). Insets show background subtracted distributions for the $\Sigma_c(2800)$. The peaks at $0.43\,\mathrm{GeV}/c^2$ are cross-feeds from $\Lambda_c(2880) \to \Sigma_c(2455)\pi$ where the pion from the $\Sigma_c(2455)$ decay is missing.

$\Xi_c(3077)$

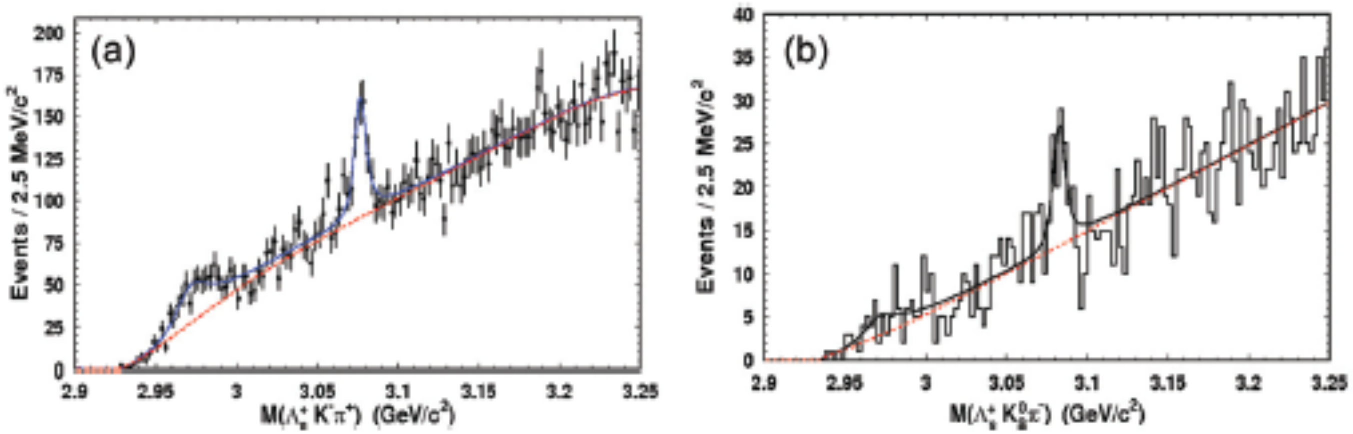


Fig. 79. Distributions of $M(\Lambda_c^+ K^- \pi^+)$ (left) and $M(\Lambda_c^+ K_s^0 \pi^-)$ (right) with the fit curves overlaid.

Table 25. Parameters of charmed baryons discovered by Belle. The $\Sigma_c(2800)$ masses were measured with respect to the Λ_c mass of $2286.46 \pm 0.14\,\mathrm{MeV}/c^2$.

Name	Quark content	Decay mode	Mass (MeV/c^2)	Width (MeV/c^2)
$\Sigma_c(2800)^0$	cdd	$\Lambda_c^+\pi^-$	$515.4^{+3.2+2.1}_{-3.1-6.0} + M_{\Lambda_c}$	61^{+18+22}_{-13-13}
$\Sigma_c(2800)^+$	cud	$\Lambda_c^+\pi^0$	$505.4^{+5.8+12.4}_{-4.6-12.0} + M_{\Lambda_c}$	62^{+37+52}_{-23-38}
$\Sigma_c(2800)^{++}$	cuu	$\Lambda_c^+\pi^+$	$514.5^{+3.4+2.8}_{-3.1-4.9} + M_{\Lambda_c}$	75^{+18+12}_{-13-11}
$\Xi_c(2980)^+$	csu	$\Lambda_c^+K^-\pi^+$	$2978.5 \pm 2.1 \pm 2.0$	$43.5 \pm 7.5 \pm 7.0$
$\Xi_c(2980)^0$	csd	$\Lambda_c^+K_S^0\pi^+$	$2977.1 \pm 8.8 \pm 3.5$	43.5 (fixed)
$\Xi_c(3077)^+$	csu	$\Lambda_c^+K^-\pi^+$	$3076.7 \pm 0.9 \pm 0.5$	$6.2 \pm 1.2 \pm 0.8$
$\Xi_c(3077)^0$	csd	$\Lambda_c^+K_S^0\pi^+$	$3082.8 \pm 1.8 \pm 1.5$	$5.2 \pm 3.1 \pm 1.8$

Summary

- Although the data taking was finished on June 30, 2010, there may be rich heavy quark physics to be analyzed in Belle data.

- Simultaneous explanation of $Z_b^{\pm}$ and $Z_c^{\pm}$ is rather difficult since heavy quark symmetry requires almost same interactions between DD^{*bar} and BB^{*bar}, but the kinetic energy of the BB^{*bar} system is much smaller than that of DD^{*bar} system.

- For the systematic studies of bottom baryons, CM energy of KEK B-factory is not enough.

- Quantum numbers, production rates, decay rates, etc. have not been determined for many higher resonance states, which should be measured.

- Super KEK B-factory will start data taking from 2016!!
- Let's enjoy heavy quark physics at Belle II